Accelerators

R. B. Palmer

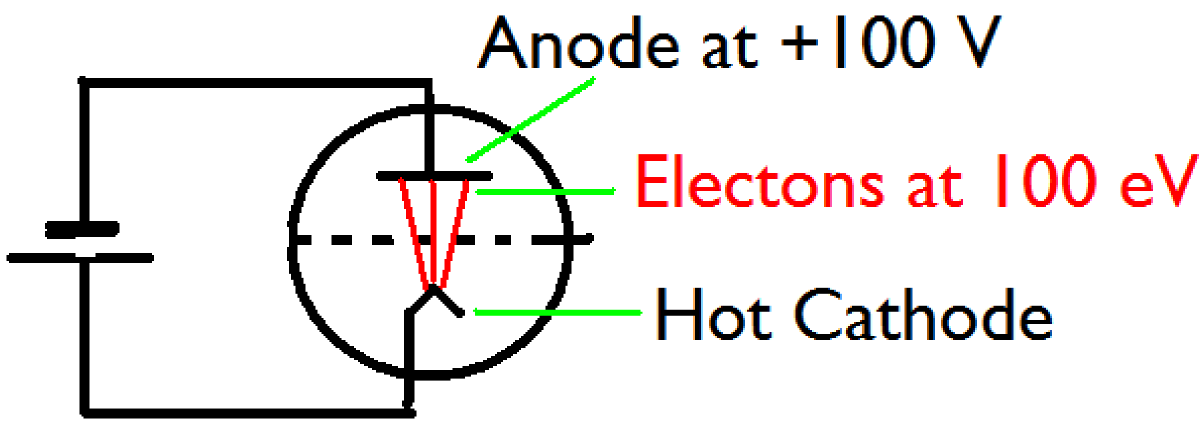
BNL 60th Birthday

- Introduction
- Early History
- Strong Focusing
- Colliders
- The Energy Frontier

INTRODUCTION

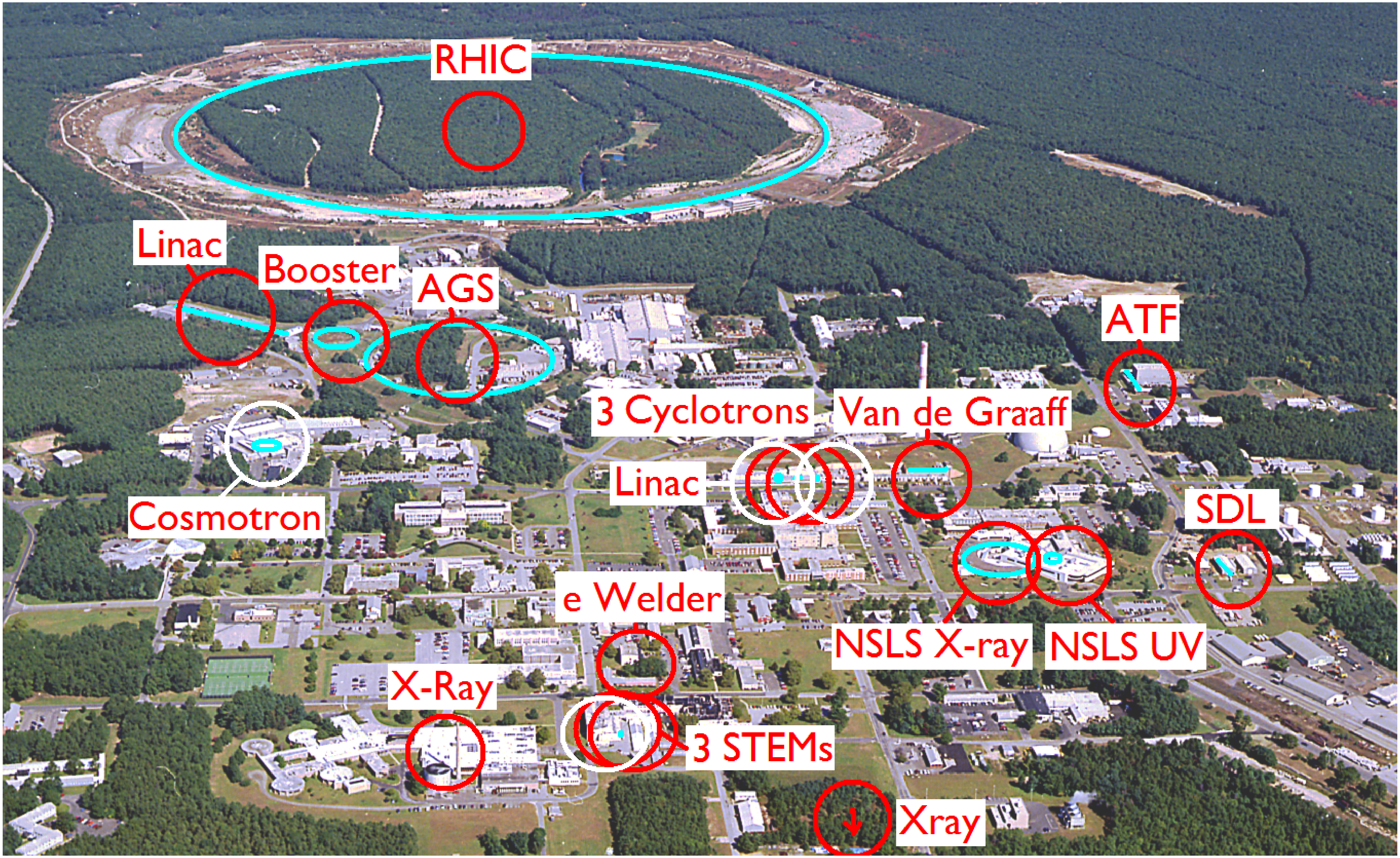
Acceleration

- Acceleration is making things go faster
- But if you push hard enough, things approach the velocity of light and cannot go much faster
- So we talk not of their speed, but of their ENERGY
- Which we measure by the volts it would need to give a election (or proton) that energy: ELECTRON VOLTS

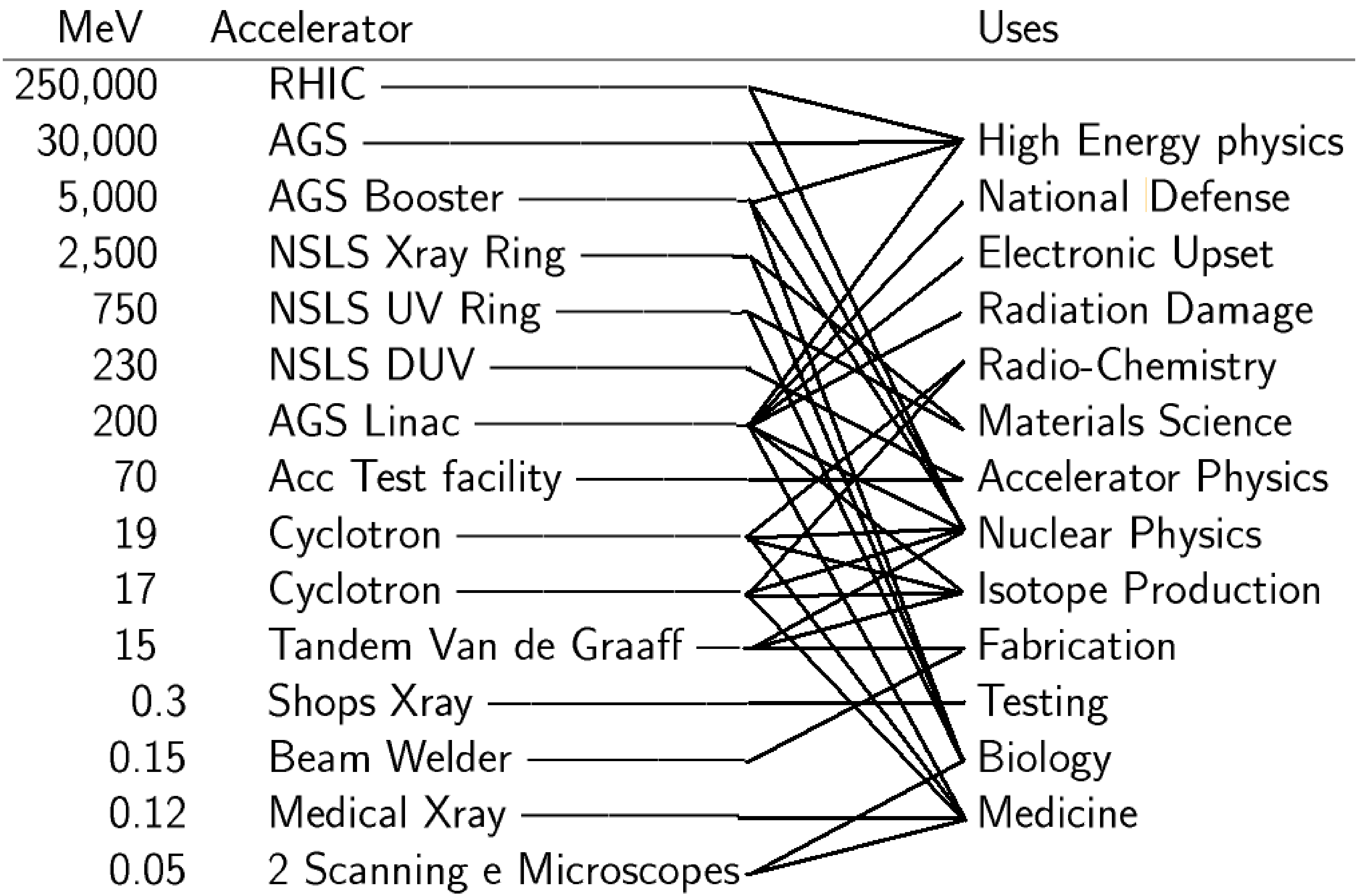


1000,000 eV = 1 MeV
1000,000,000 eV = 1 GeV
1000,000,000,000 eV = 1 TeV

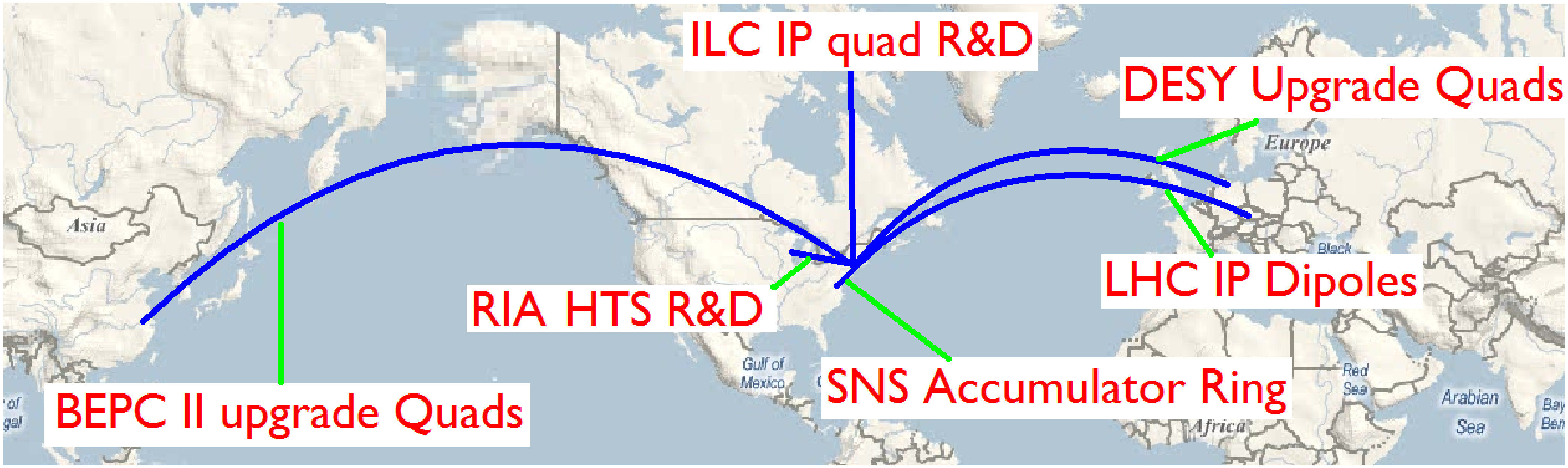
Accelerators are everywhere at BNL



And they do everything

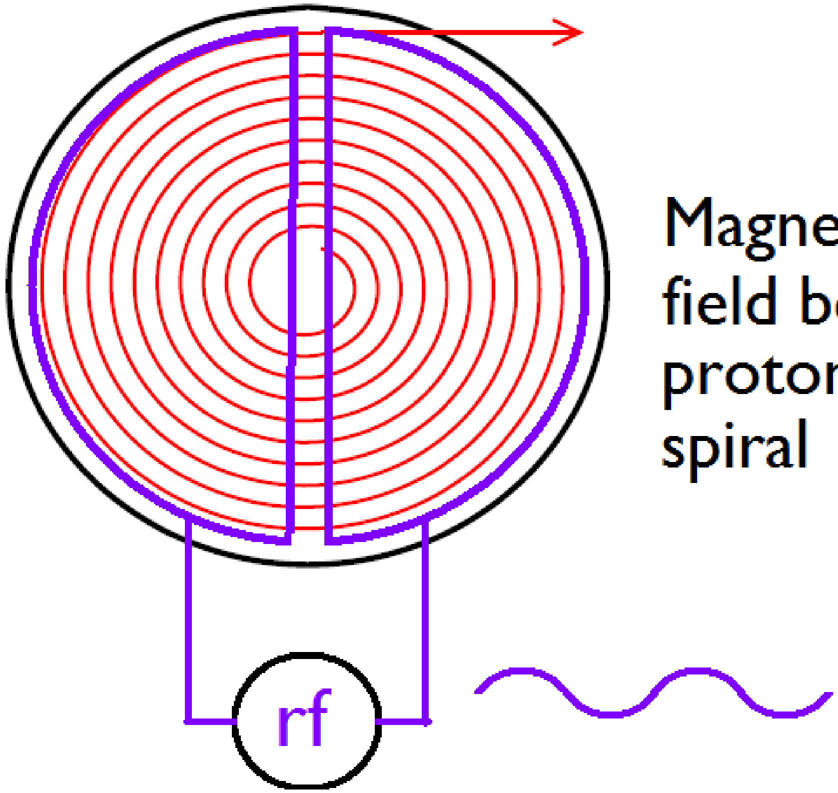


BNL made equipment and R&D for many others



EARLY HISTORY

1930 in Berkeley The Cyclotron Concept



Magnetic field bends protons in spiral

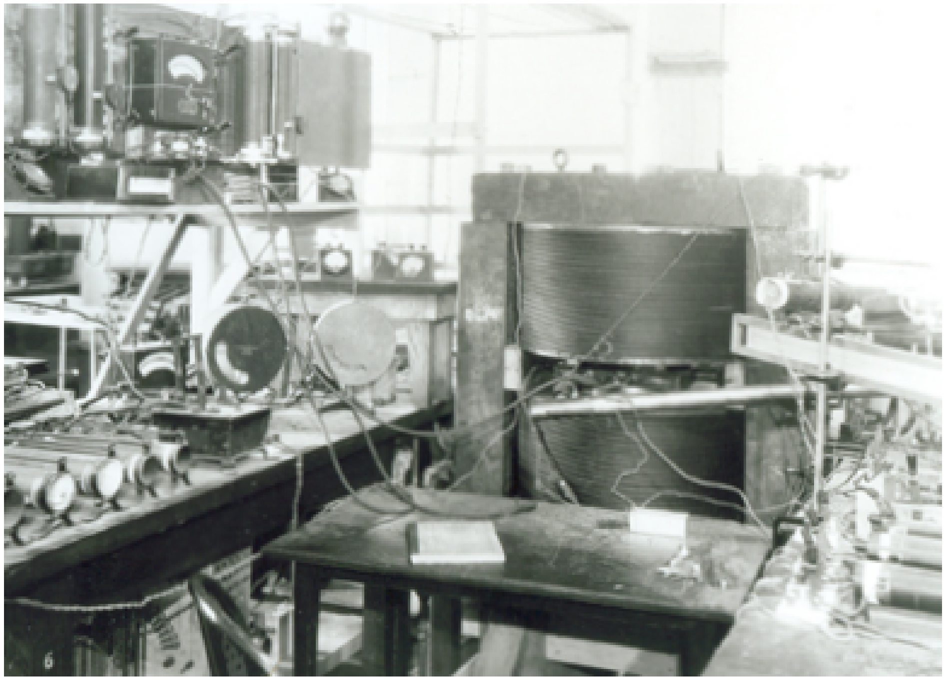
Alternating voltage gives many kicks

Laurence

The principal of all circular accelerators: particles are in resonance with the radio frequency acceleration voltage.

But Laurence could not make it work till he got a good student.

1931-1932 in Berkeley The First Cyclotrons



11" Cyclotron

Livingston

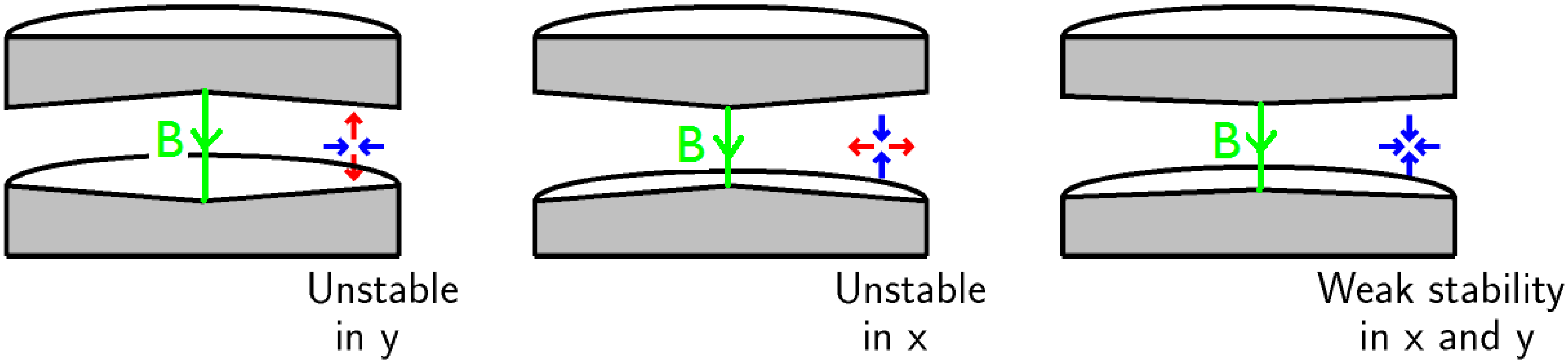
1931	4"	Cyclotron (with no focusing)	80 keV
1932	11"	Cyclotron (with magnetic focusing)	1.22 MeV

"Lawrence was my teacher when I built the first cyclotron
He got the Nobel Prize for it - I got a PhD"

But it was Lawrence's idea

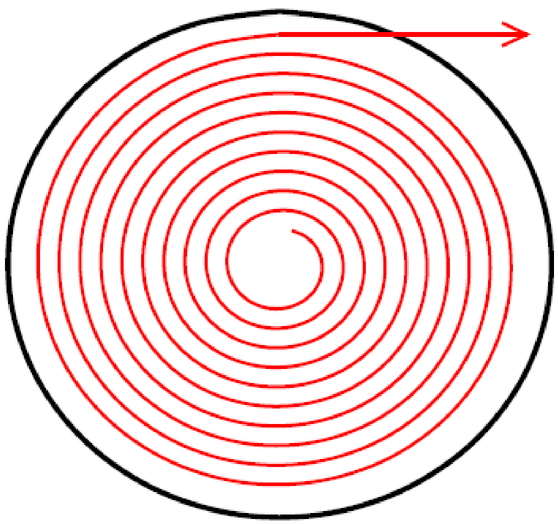
Magnetic Focusing

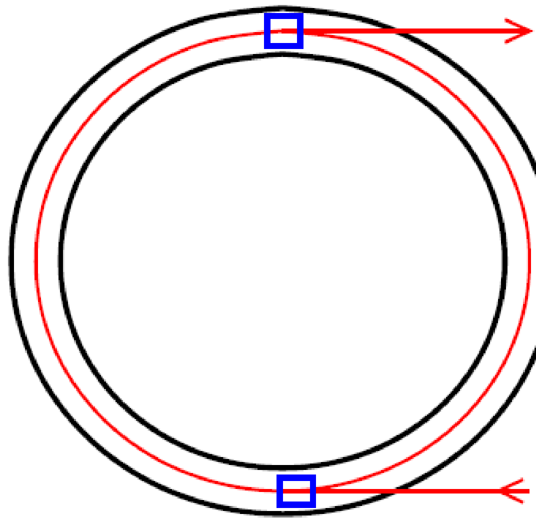
Livingston discovered magnetic focusing experimentally, using shims.



At the time this was not called "weak", it was stronger than the rf field focusing that was the only kind available for linear accelerators

1945 Cyclotron → Synchrotron



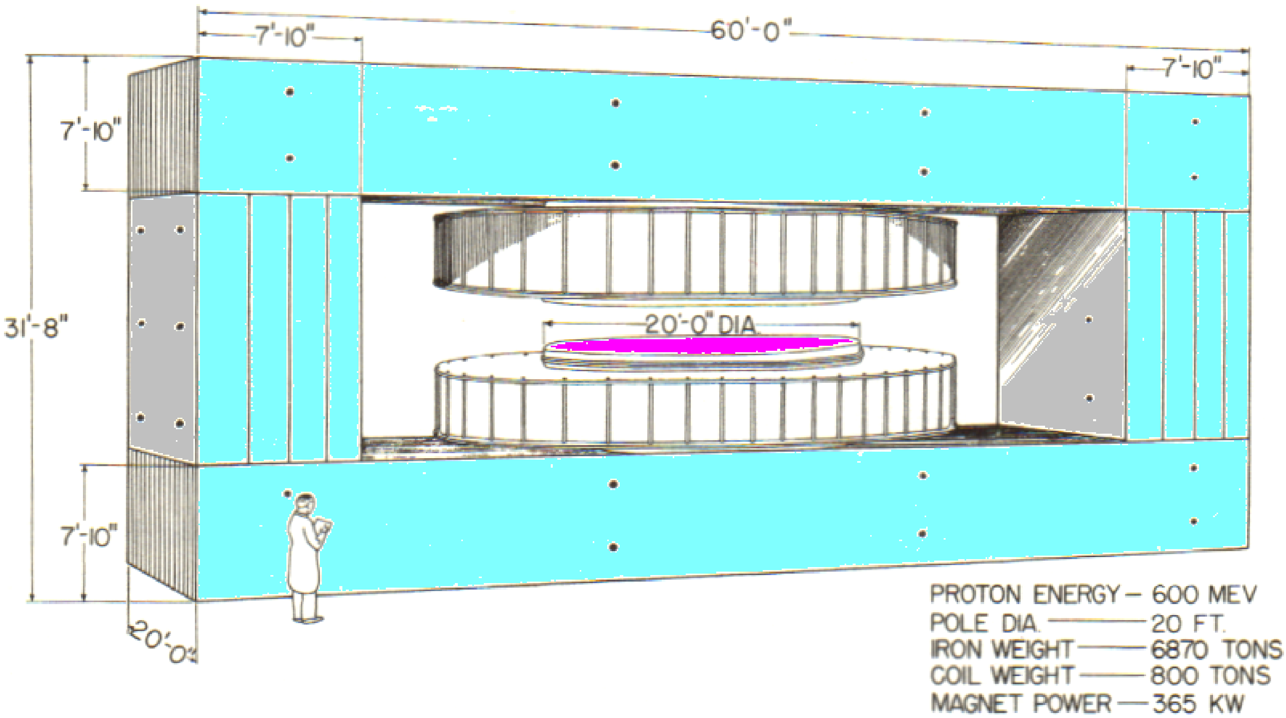


Oliphant

Marcus Oliphant, an Australian, invented the synchrotron while in Berkeley in 1945 and proposed it to the UK Atomic Energy Directorate after the war.

In 1953 his machine, (just less than 1 GeV) finaly ran, but it was not the first. By then the BNL Cosmotron had been running for over a year.

1946 Brookhaven Plans



Rabi

Livingston was to lead the BNL Accelerator effort: a Van-de-Graaff, a 60" cyclotron, and something bigger.

Livingston wanted to build a 240 inch Cyclotron. Rabi, a trustee, wanted a higher energy Synchrotron. Livingston said it might not work. Rabi said "go for it". Livingston left. BNL build a Synchrotron.

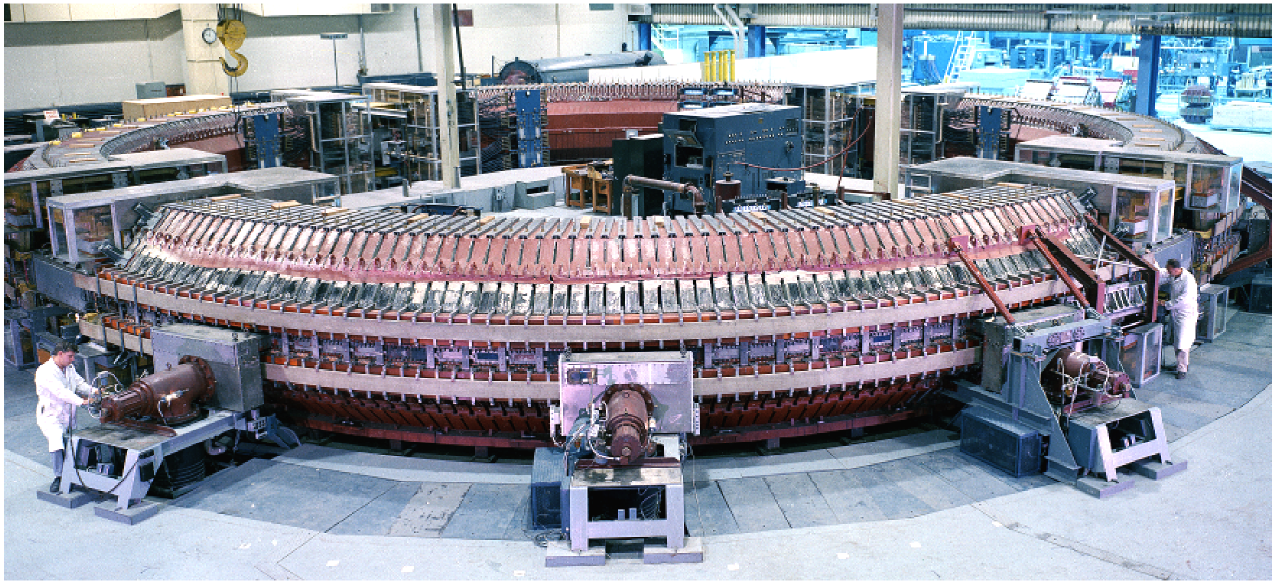
Cosmotron

The AEC supported two machines: a 3 GeV at BNL and a 6 GEV machine at Berkeley. Berkeley decided to build a 1/4 model first.

BNL went straight ahead, choosing a 25" x 6" beam aperture.

Then the Berkeley model indicated that this was too small, and they picked 168" x 48". It was too late for BNL to change.

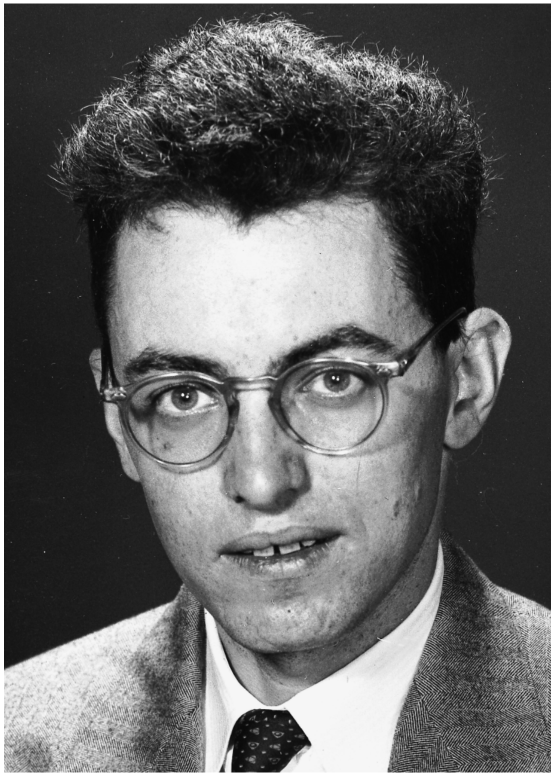
But the Cosmotron worked just fine! It ran first in 1953 even before Oliphant's. Berkeley was amazed and revised their aperture down from the 168" x 48" Jeepatron to 48" x 12".



STRONG FOCUSING

The 1952 Revolution

In Europe, CERN was established and, before the Cosmotron had run, their accelerator experts came to BNL to learn how to build such a machine.

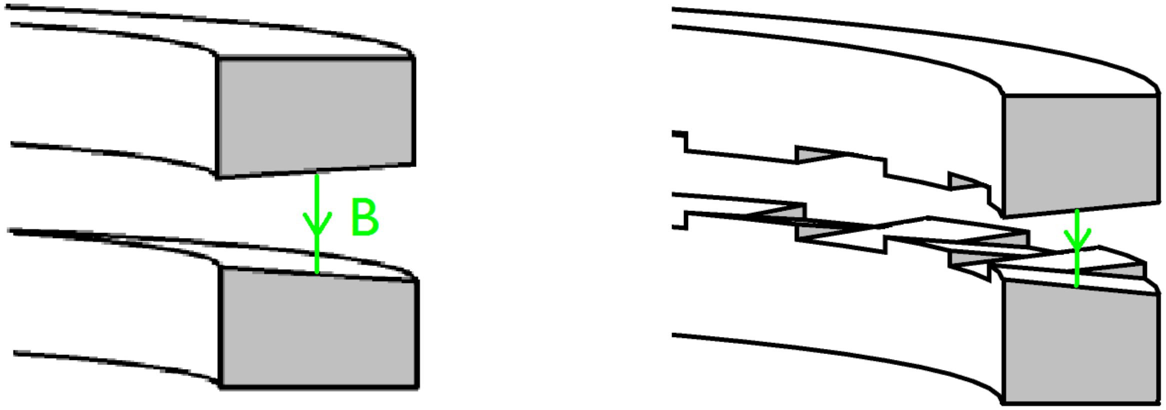

Courant


Snyder

Livingston, visiting BNL from MIT, wondered if the Cosmotron could be improved if some of the C magnets were reversed, but feared that the resulting alternation of gradients would hurt.

Courant and Snyder discovered that it helped a lot ! "Strong Focusing" was invented, together with a whole new mathematics to study it with.

Strong Focusing

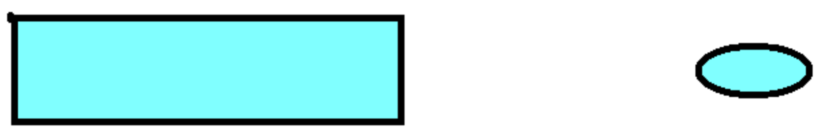


Old Style — Alternating Gradient Synchrotron

"Weak" Focus — Strong Focus

Stong focusing allows much smaller beam dimensions, and thus smaller magnets. For the cost of a 10 GeV weak focus machine, one could build a 25 GeV one.

Beam Pipe sizes

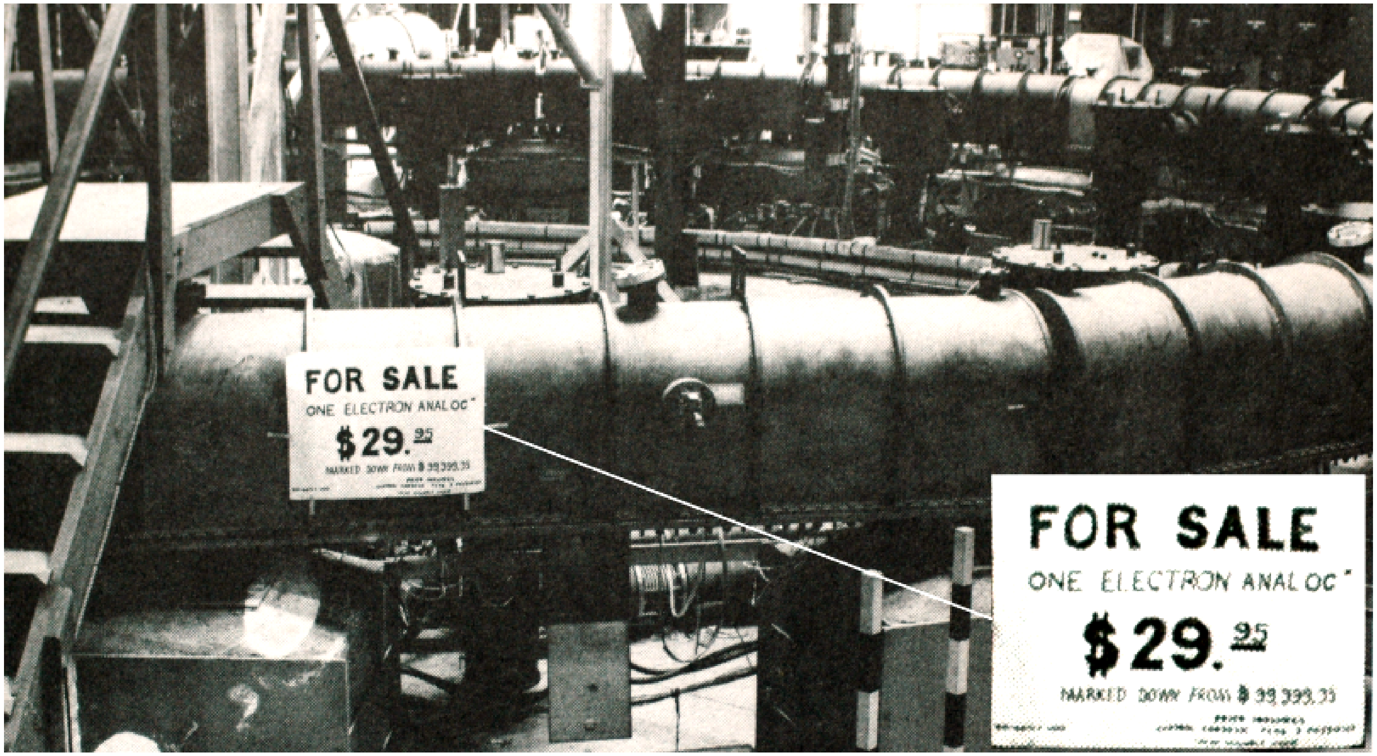


Weak Focus — Strong Focus

Cosmotron — AGS

Electron Analog

With Strong focusing, particles pass through an unstable "transition". Fearing that this might not work, BNL decided to build an 'Election Analog'.



CERN, with greater courage, decided to go ahead at once with their PS, and thus beat BNL. The Analog worked fine, though transition remains a source for losses in all machines that have it.

Cornell, with a strong focus electron machine got there even before CERN.

Christofilos

In fact, Christofilos, a Greek elevator operator and self taught scientist had invented strong focusing almost 2 years earlier. His paper, sent to Berkeley, had been assumed crazy.

On a visit to the US, in the Brooklyn library, he chanced to read Courant-Livingston-Snyder's paper and called BNL. He was invited to visit. When they realized the truth, he was hired on the spot.

At Livermore, he later invented Induction Linacs and the Astron plasma confinement.

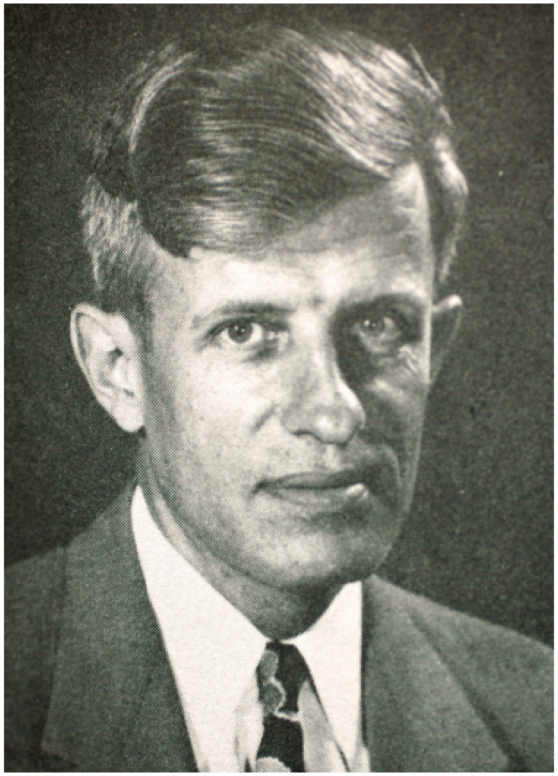
1960 The Alternating Gradient Synchrotron (AGS)

In 1960, just a year after the CERN Proton synchrotron (PS), the AGS started operation. As you will hear, it has been one of the most productive "Engines of Discovery" ever built, and it is still running as an injector into RHIC.

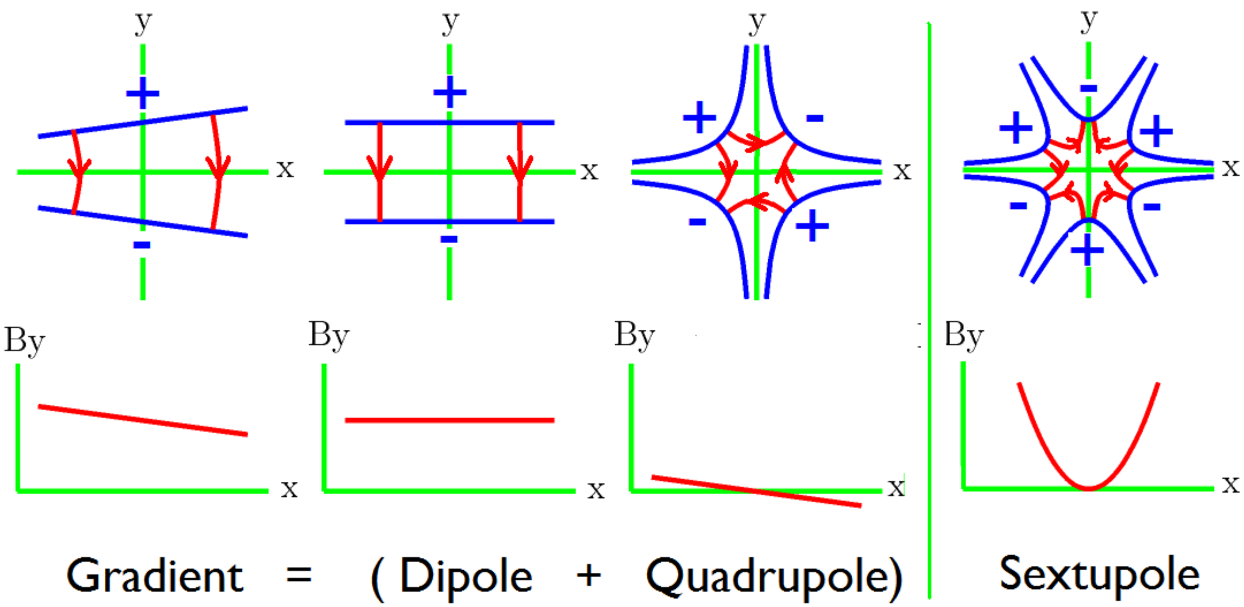
Lattices

Courant and Snyder's discoveries and theory led to a whole new art/science of lattice design

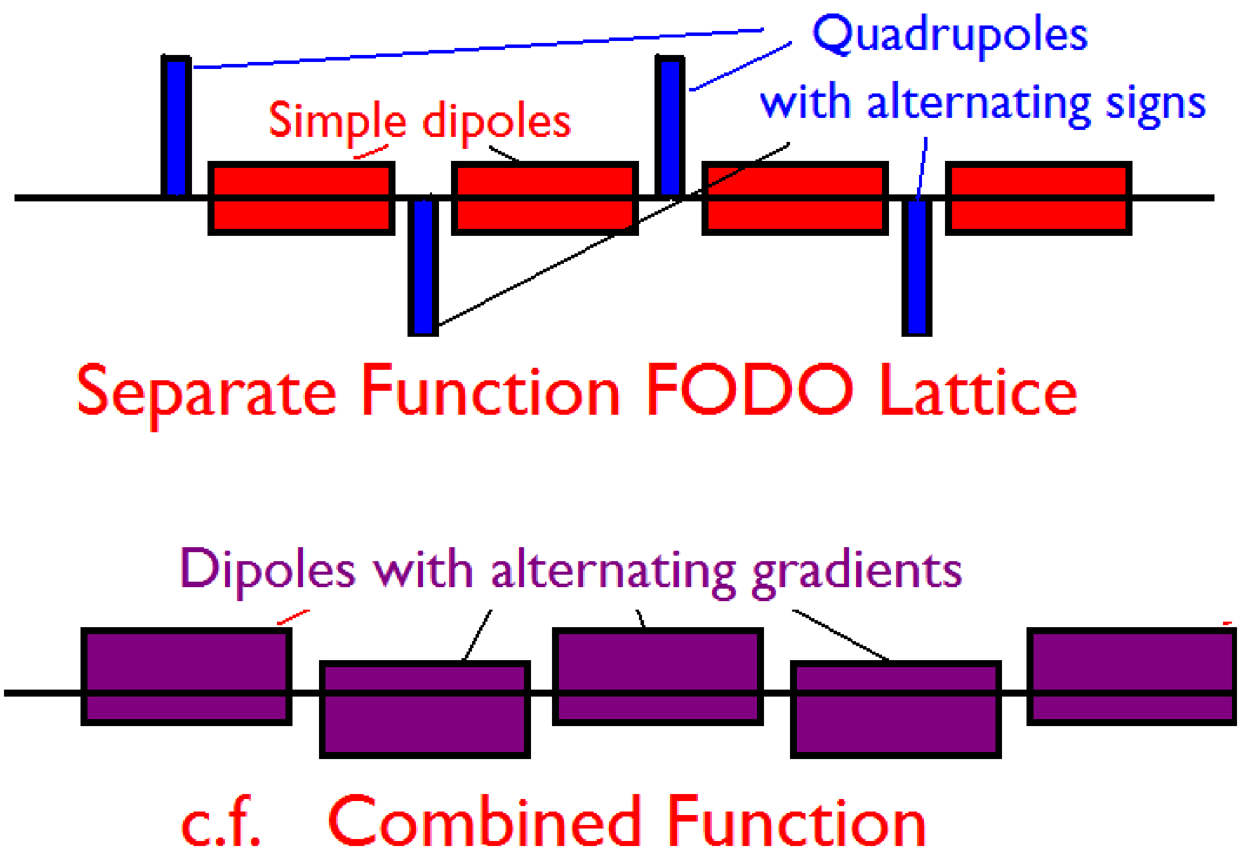
- Instead of alternating gradients one can have dipoles and alternating quadrupoles
- Blewett proposed linear accelerators focused by alternating quads (without dipoles).
- With sextupoles, came "chromatic correction"
- More specialized lattices were invented (next)

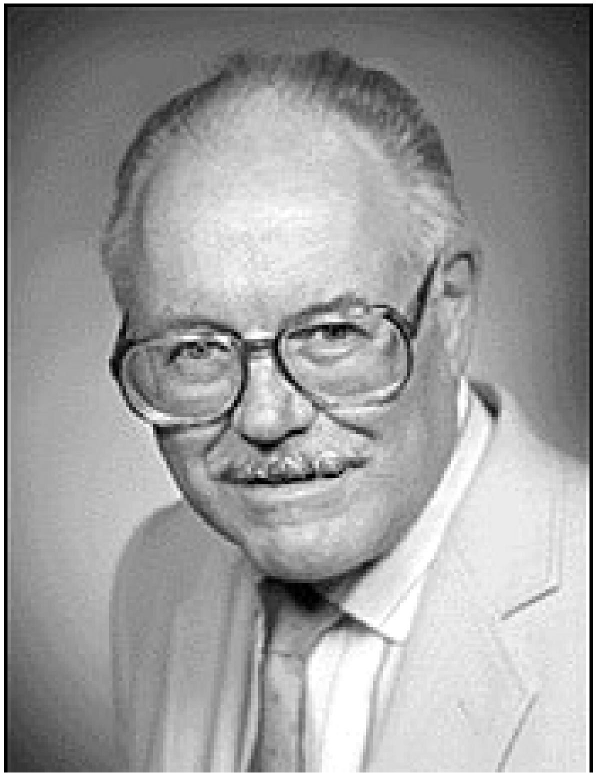


Blewett



1) FODO: Separated Function Lattice





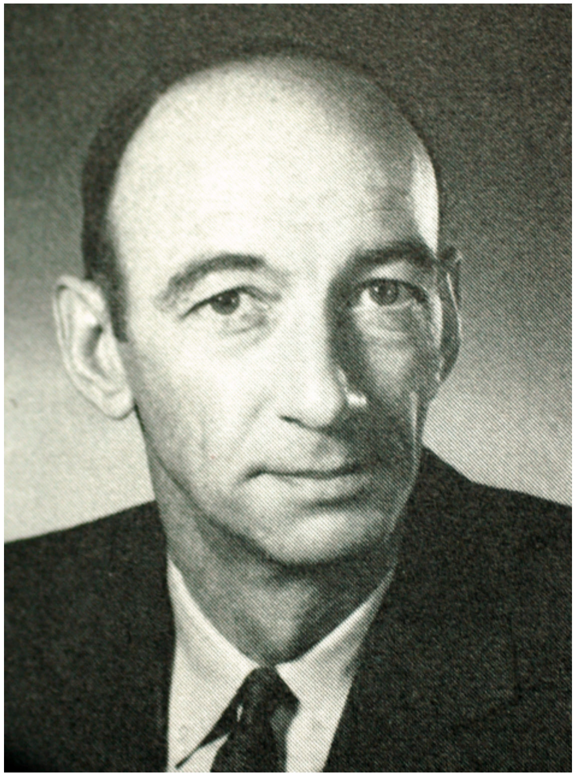
Danby

Allows separate control of bending and focus. This, with the addition of sextupoles, is now the 'standard' bending lattice.

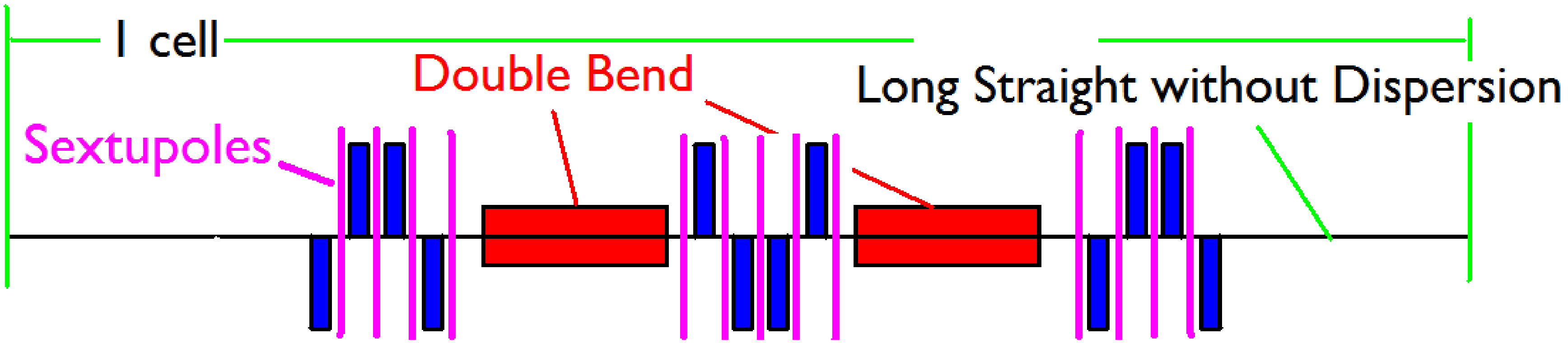
2) Chasman Green

Used in Light sources: the Double Bend Achromat is designed to give small quantum fluctuations and provide dispersion free "straights" for other equipment (NSLS NSLS II, ESRF Grenoble, APS Argonne, Spring-8 Japan)

Chasman



Green

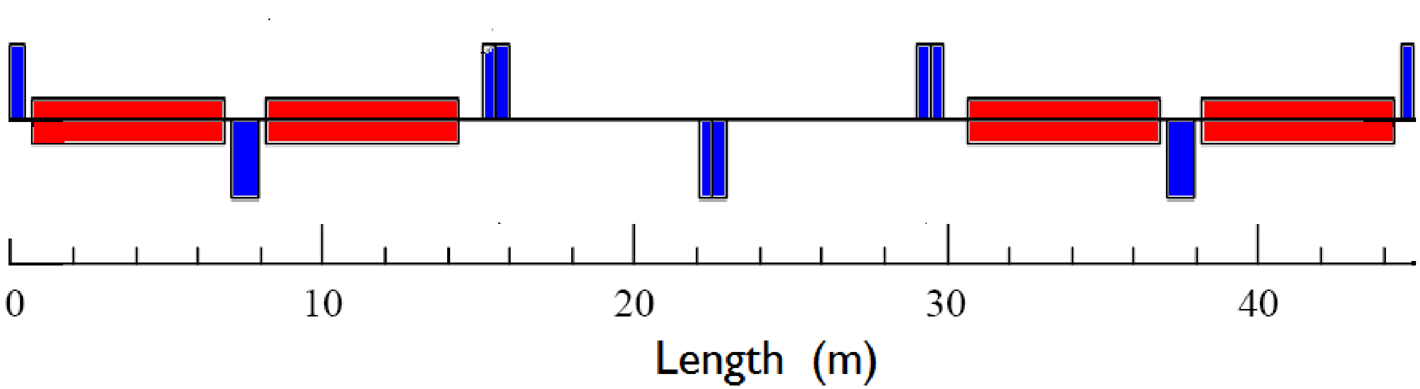


3) Variable Momentum Compaction

Trbojevic

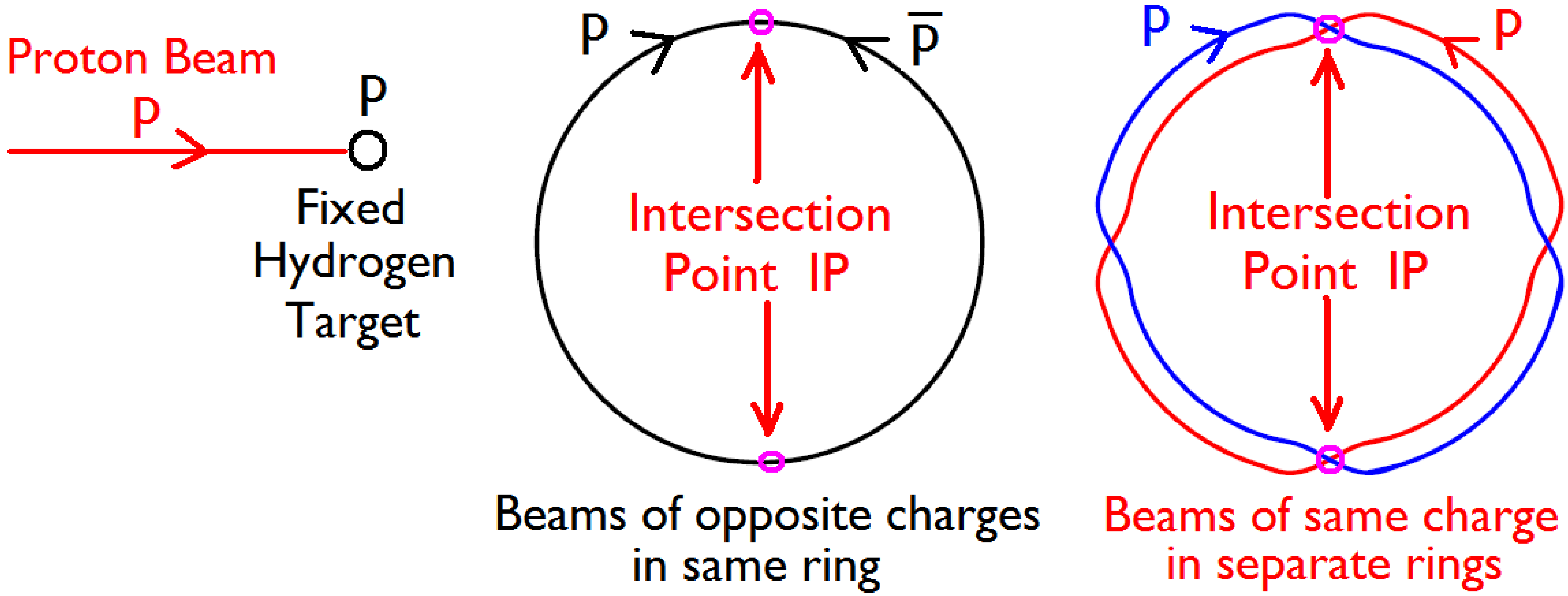
Eliminates the "Transition" & Reduces losses

- Design when at FNAL for the Main Injector
  But rejected by them.
- Design for SSC
  But rejected by them too.
- Used in ANKA light source in Germany.
- To be used in JPARC 50 GeV p synchrotron



COLLIDERS

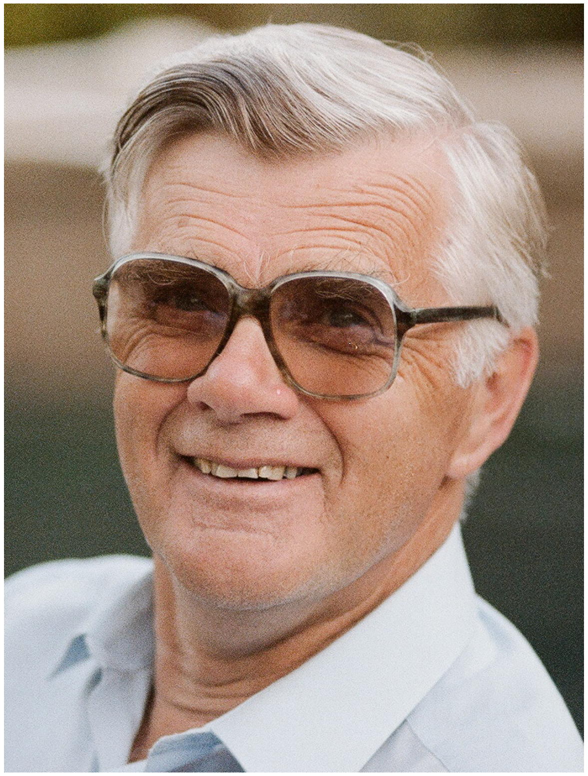
Collider types



- From relativity this gives huge gains in effective energy
- Single proton-antiproton ring is cheaper and already exist
- But making enough antiprotons is harder giving lower luminosity

1969 First p-p (Two Ring) Collider: 30 GeV ISR

ISR at CERN, Switzerland



Johnsen
Later at BNL

The ISR, built with incredible care, and worked incredibly well.

Leading, later, to the decision for BNL to build a 400 GeV ISA to be called "Isabelle", but the invention of $\bar{p} - p$ gave competition.

1994 The 1st p-$\bar{p}$ Collider: 400 GeV SPPS

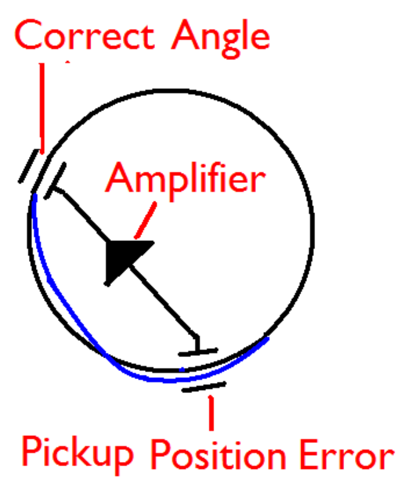
CERN, Switzerland

The problem is making and "cooling" the anti-protons ($\bar{p}$'s).

Van der Meer invented Stochastic Cooling in transverse directions.

Rubbia

Van der Meer



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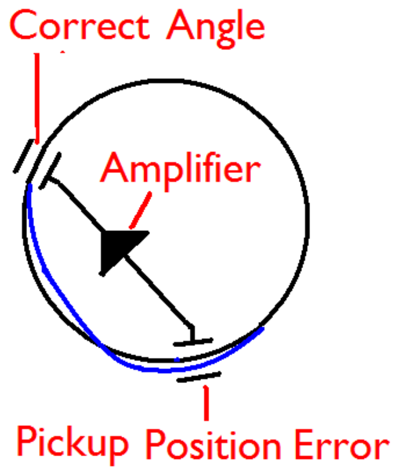
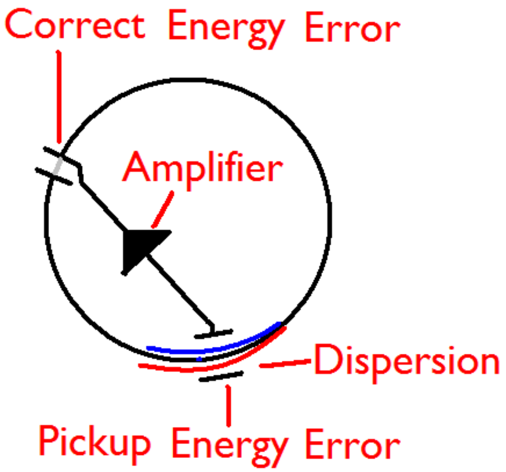
In a workshop at BNL, I suggested the extension to cooling momentum, and was acknowledged!

Rubbia

Van der Meer

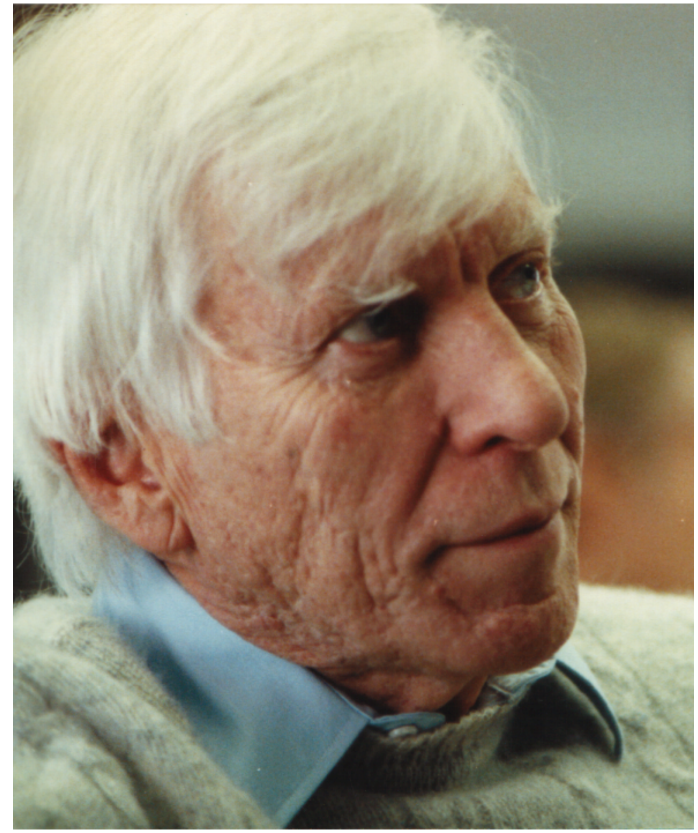




1994 The first p-$\bar{p}$ Collider in US TeVatron

Wilson

Edwards

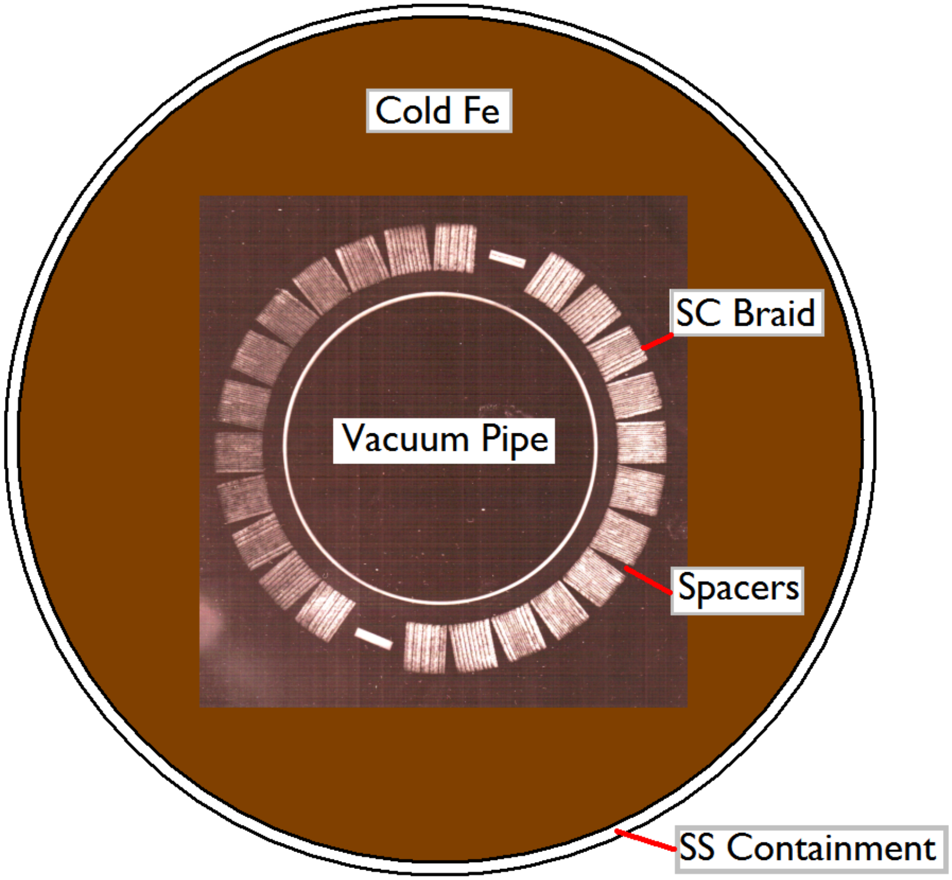


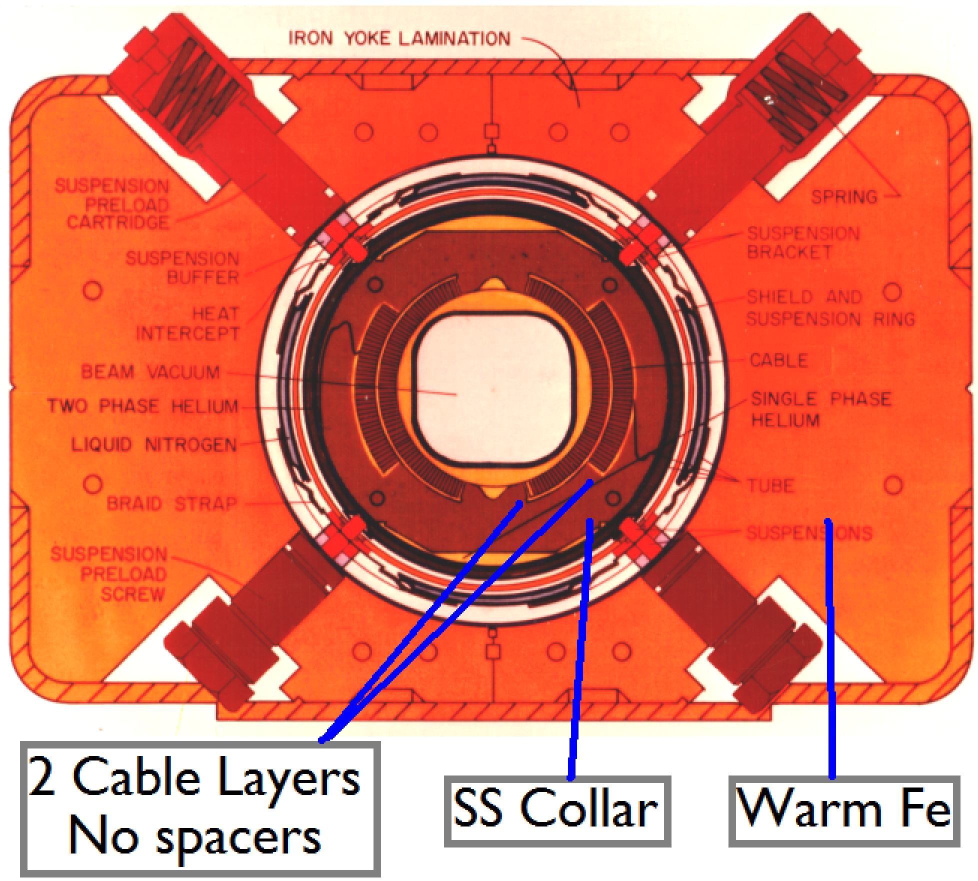
Tollestrup

The TeVatron, using superconducting magnets, was built by Wilson in 1982 as an "Energy Saver" for the FNAL 400 GeV accelerator. With stochastic cooling, it was converted (1994) to an antiproton-proton collider like the SPPS, but at 1000 GeV (1 TeV).

This became a direct competitor with Isabelle

In US: Isabelle at BNL vs. TeVatron at FNAL



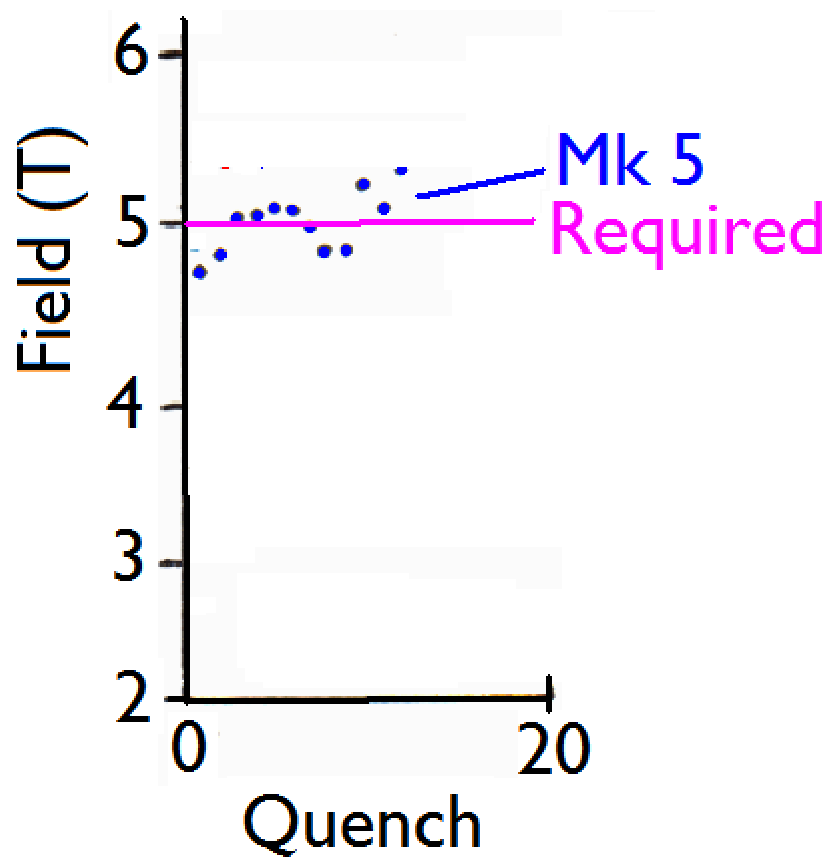


Isabelle
BNL
proton-proton
High Luminosity
400 GeV

TeVatron
FNAL
proton-antiproton
Low Luminosity
1000 GeV

Isabelle Magnet Performance at BNL

After some initial magnet success at BNL, the design field was raised from 4 to 5 T. Production was then handed off to Grumman. By the 5th industrial magnet, the desired field was reached.



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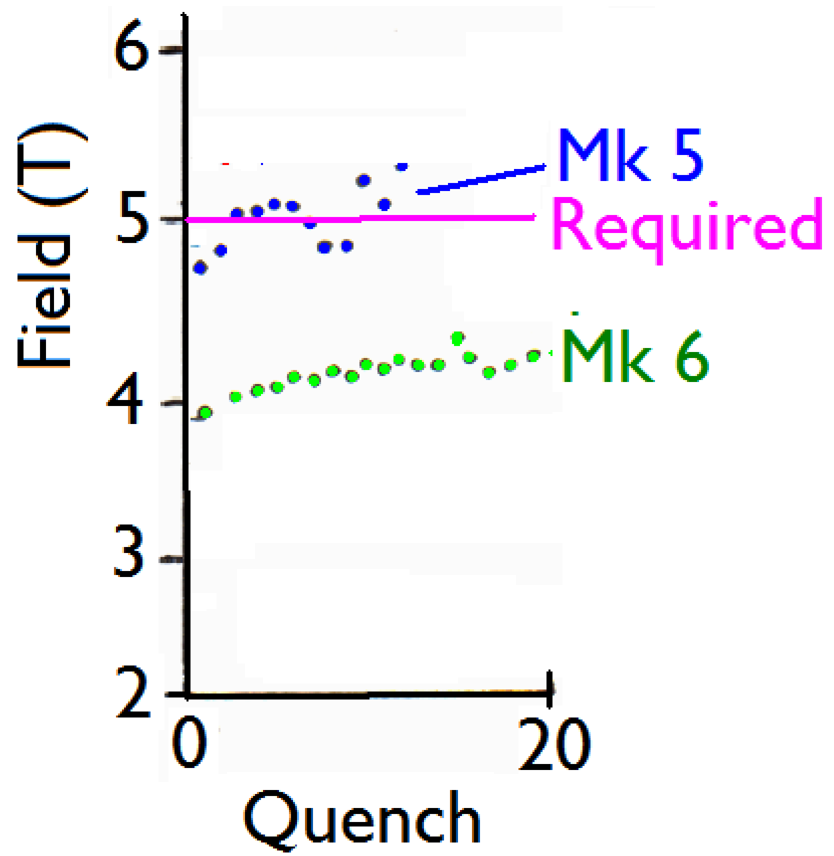
But the next did not do so well

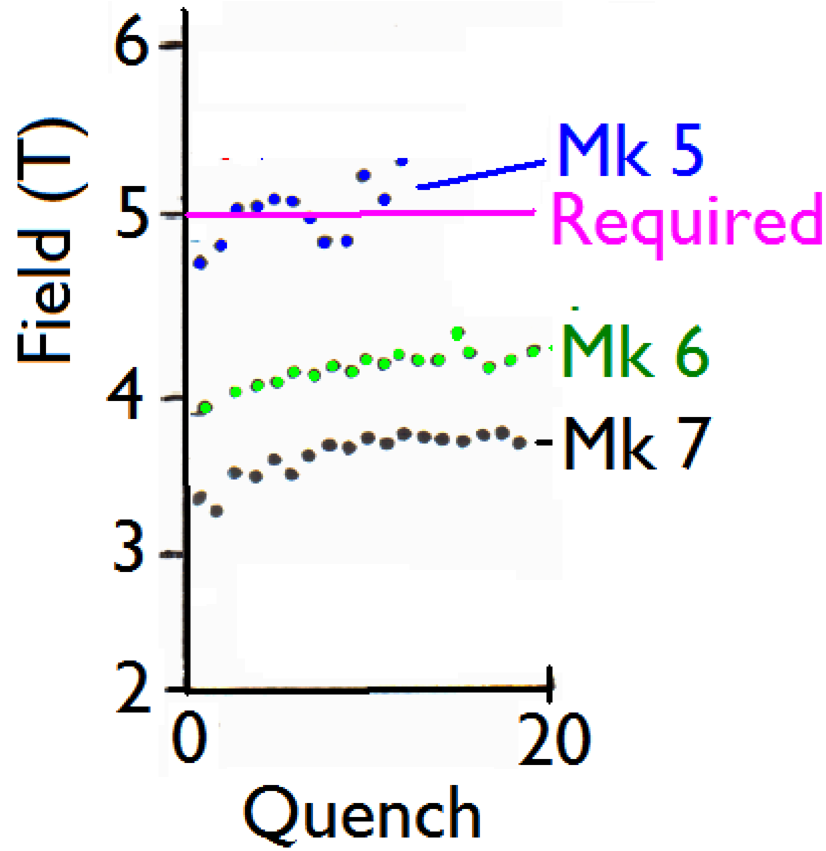


Isabelle Magnet Performance at BNL

After some initial magnet success at BNL, the design field was raised from 4 to 5 T. Production was then handed off to Grumman. By the 5th industrial magnet, the desired field was reached.

But the next did not do so well

And the next did worse.
Mk5 was never reproduced.

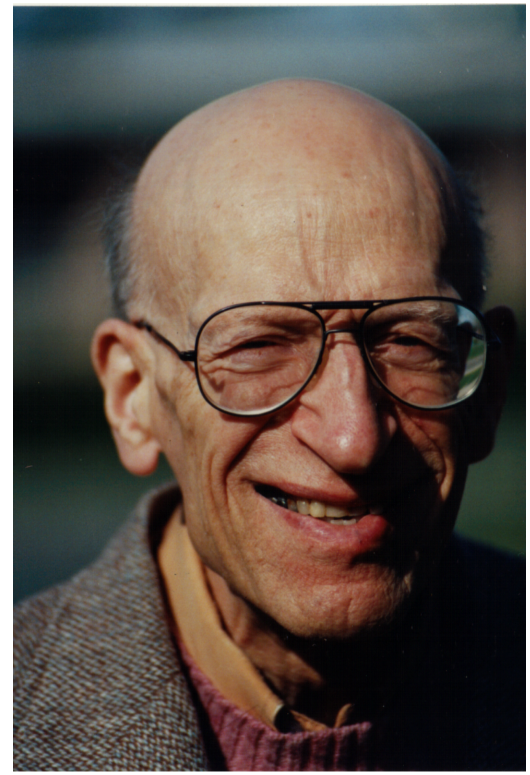


Lab management kept claiming that it now understood the problem, and that the next magnet would prove it. Those who claimed otherwise were told to keep quiet, but eventually a committee under Forsythe was formed to study the problem.

Palmer Magnet

Goodzeit

Samios

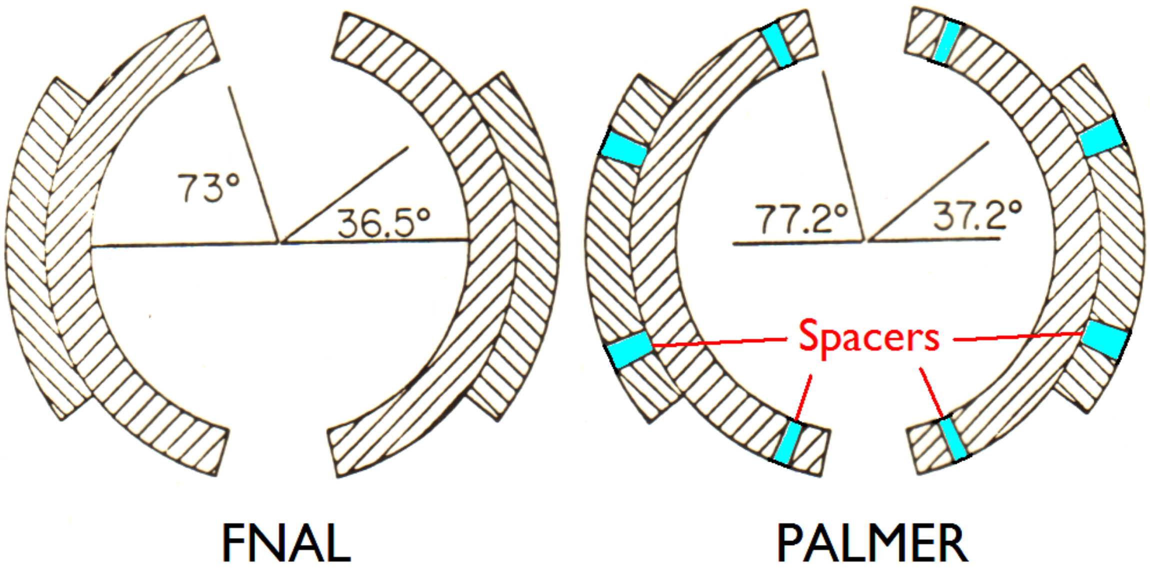


Shutt

The committee agreed that a new approach was needed, but not on what that approach should be. A small group of us in Physics believed we had the answer. Samios could provide only 30 k$, about 1/10th of what was needed, but we started anyway.

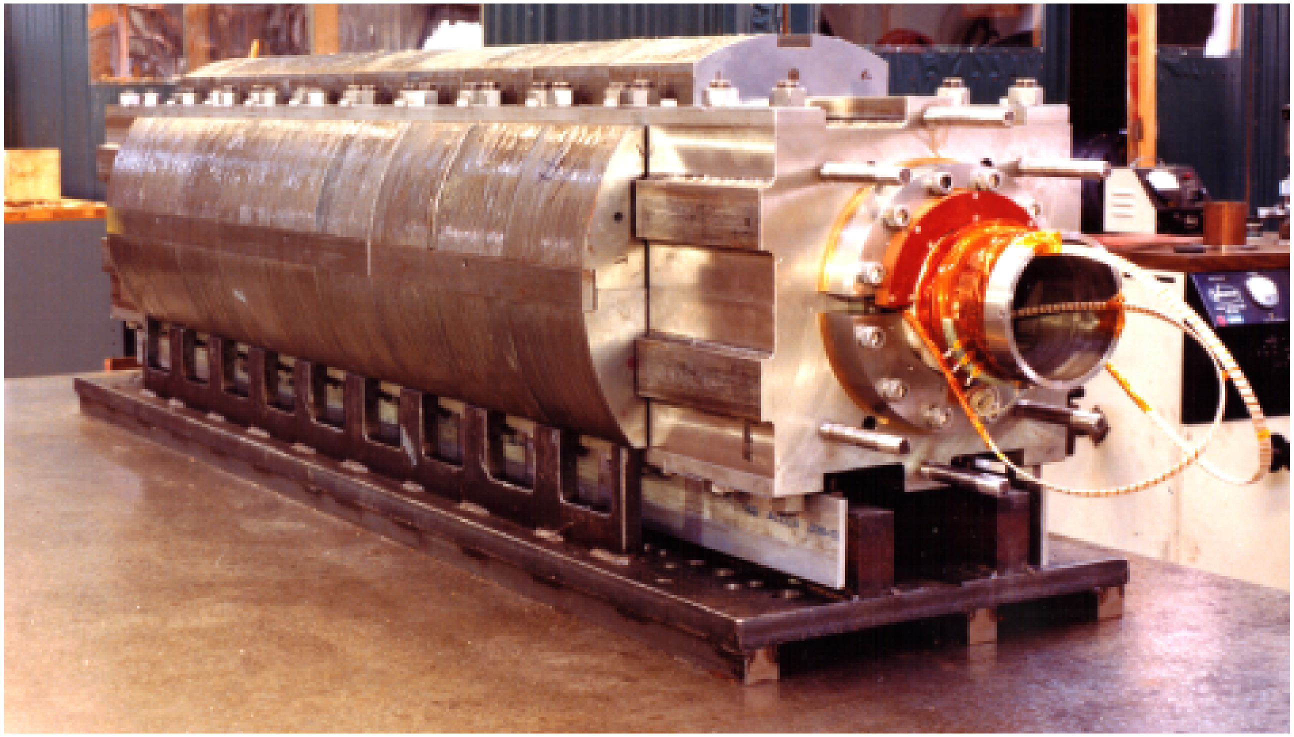
The alternative design

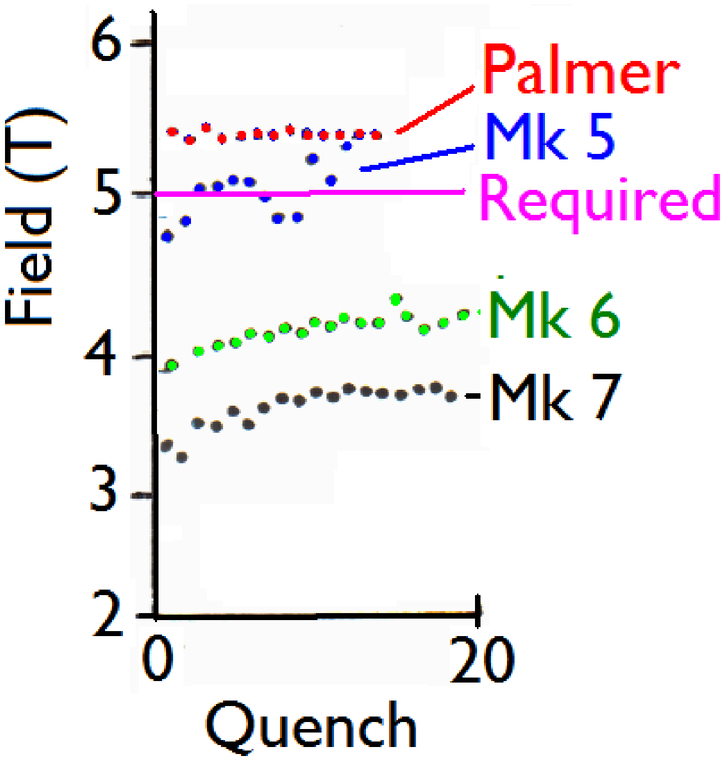
- Use 2 layers of Cable (as in TeVatron) free from friends
- Add spacers (as in Isabelle) to get required field quality
- Use Cold Iron (as in Isabelle) to support coil forces
- Split the iron and apply pre-compression with bolts (new)



Since we had no priority in the BNL shops, we machined our parts at the MIT Magnet Lab (thanks to Marsden). And when we needed it, we discovered we had a secret priority with BNL shop's Bob Lehn. Marsden, conveniently, did not send BNL the bills till after the magnet was complete. The total was nearly 300 k$!

6 Months later it worked perfectly

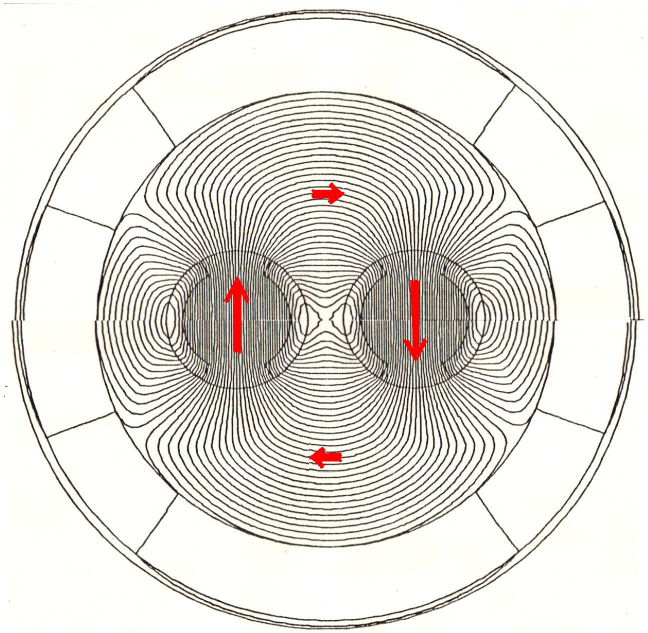




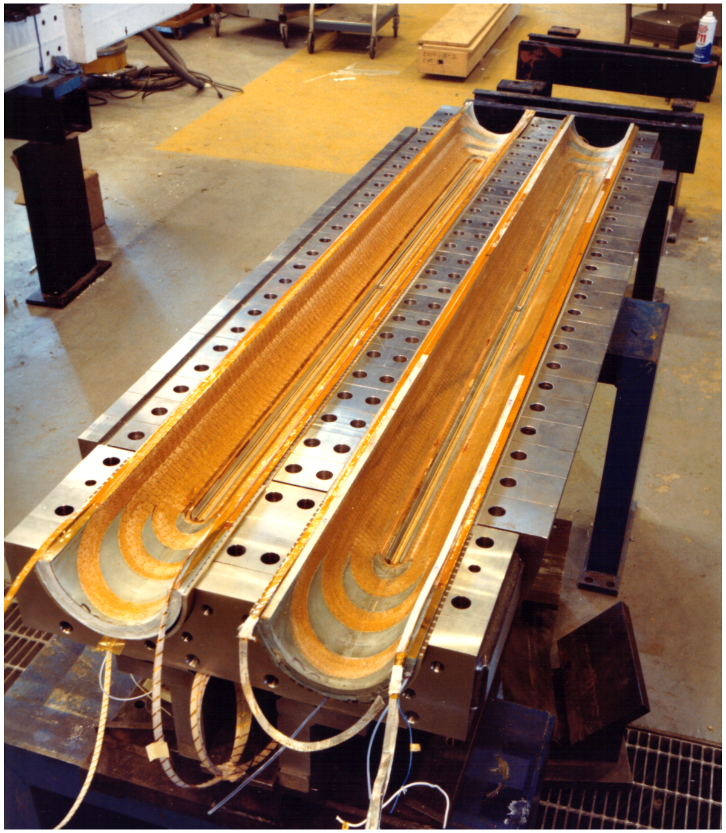
- Samios became the Lab Director
- Nobody worried about the 300 k$
- Subsequent magnets worked almost as well

But it was too late, Isabelle was canceled and we started work on the SSC. Then SSC was canceled. But all was not lost, what had been learned became part of RHIC.

Another idea not lost: 2 in 1



- Mount 2 dipoles in one Fe yoke
- Uses less Fe
- And less SC
- Lower cost

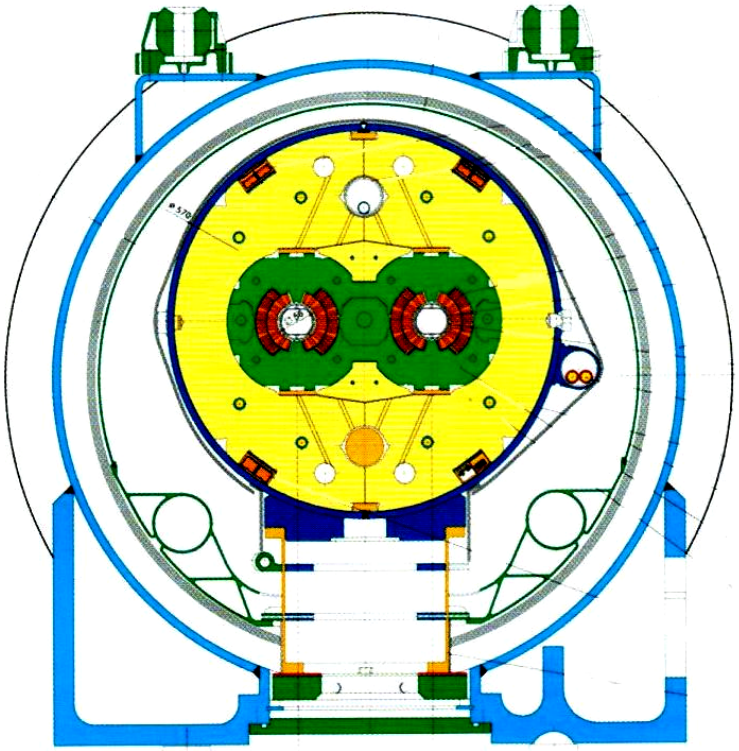


- Built prototypes for Isabelle
- Isabelle rejected them

- Built prototypes for SSC
- SSC rejected them

- But the LHC chose them
  If LHC fails, you know who to blame

CERN Switzerland 7 TeV Large Hadron Collider (LHC)



Due to operate next year, it will be the world's highest energy machine. The US, including BNL, played significant roles in its construction, supplying special magnets for its intersection regions, and supporting startup and R&D for future upgrades.

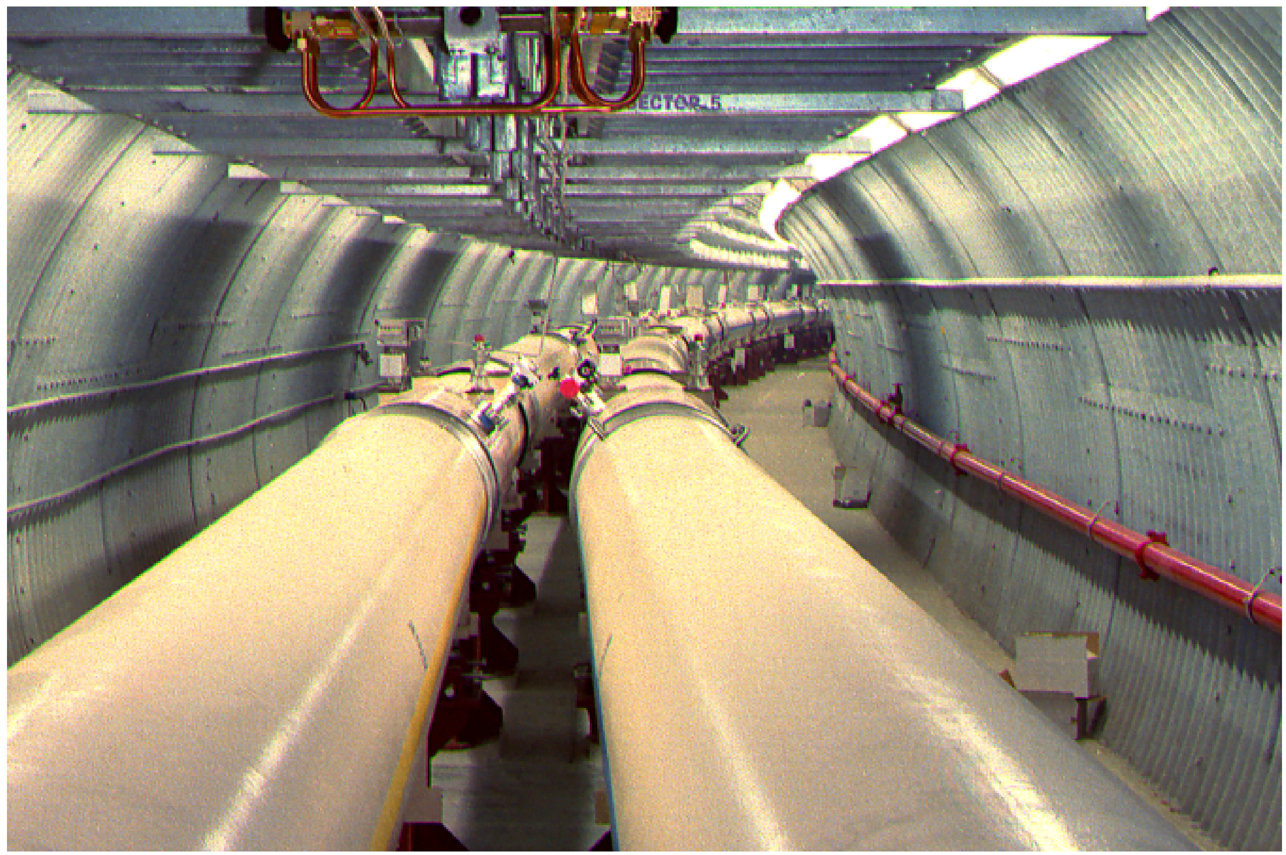
In the mean time BNL got the

250 GeV Relativistic Heavy Ion Collider (RHIC)

- Used Isabelle tunnel
- Isabelle refrigerator
- Isabelle magnet ideas
- But was not Isabelle

And RHIC, studying Heavy-Ion Heavy-Ion collisions, has proved far more exciting than Isabelle would have been.

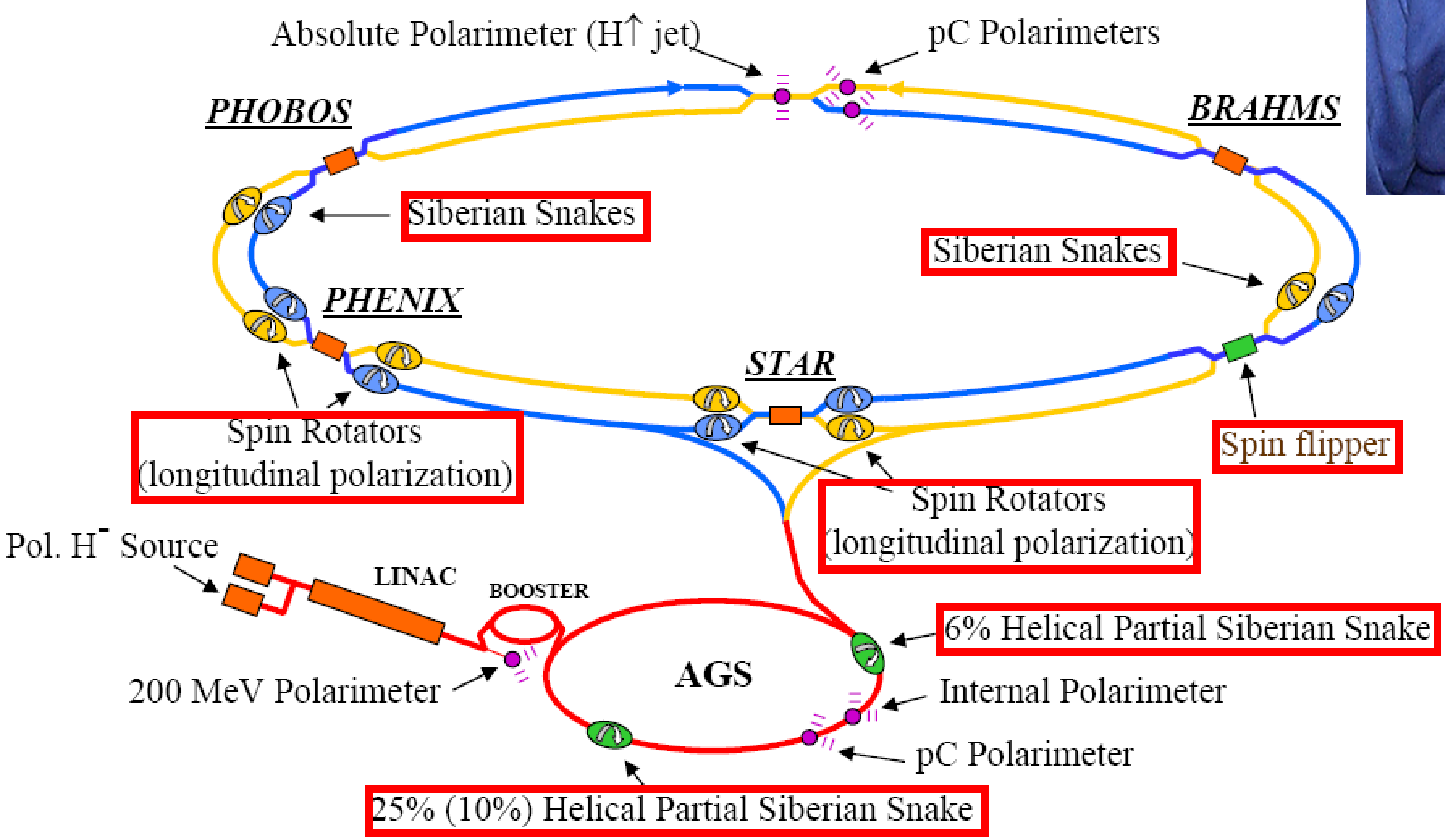
Ozaki



Spin in RHIC

RHIC has continued the planed Isabelle study of the spin dependence p-p interactions. To do this required elaborate and subtle spin manipulations to avoid the 1000 or more spin destroying resonances.

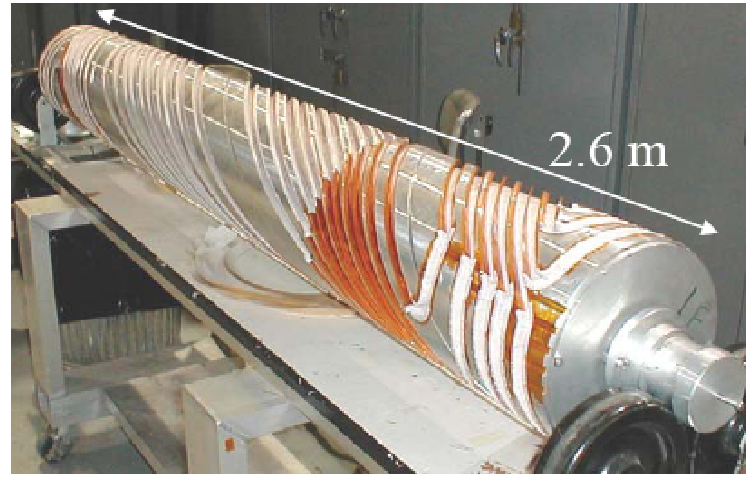
Roser



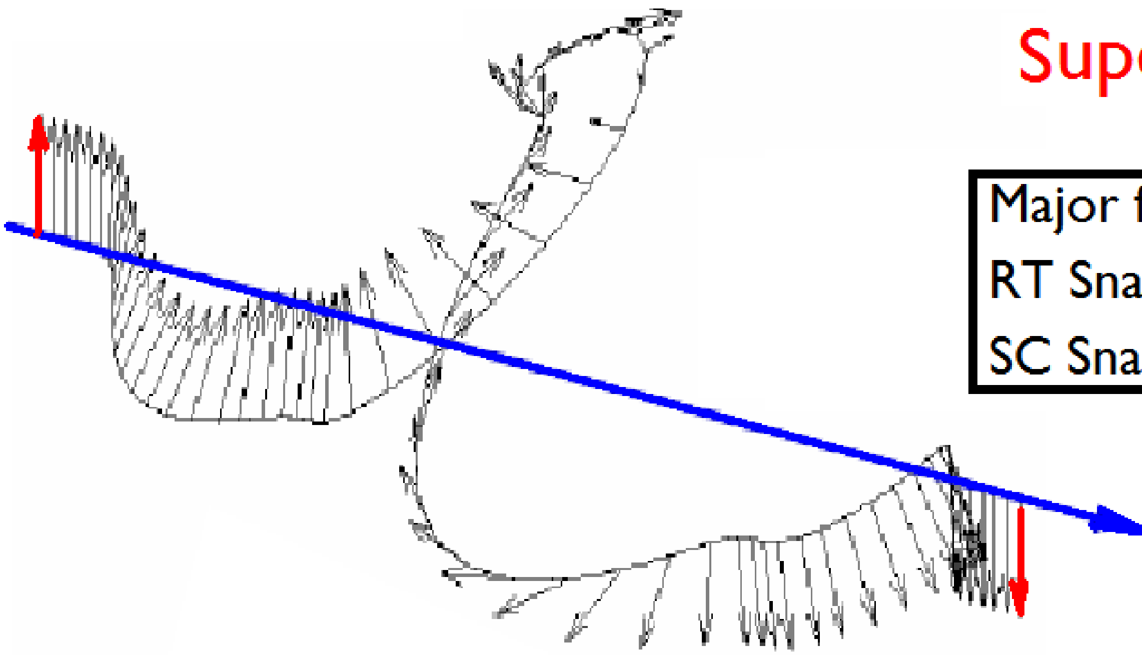
What are these Siberian Snakes ?

Proposed by Derbenev and Kondratenko in Novosibirsk in 1974

Room Temp Snake



Superconducting Snake



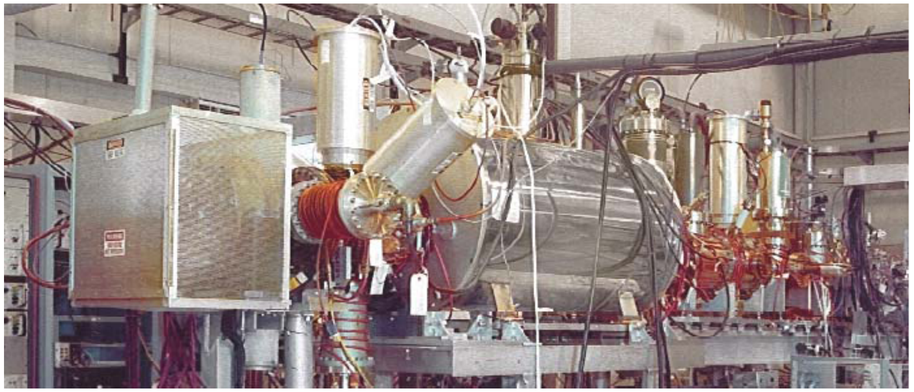
How the spin evolves through a snake

Major finding from RIKEN, Japan
RT Snake from Tokano Ind., Japan
SC Snake from BNL

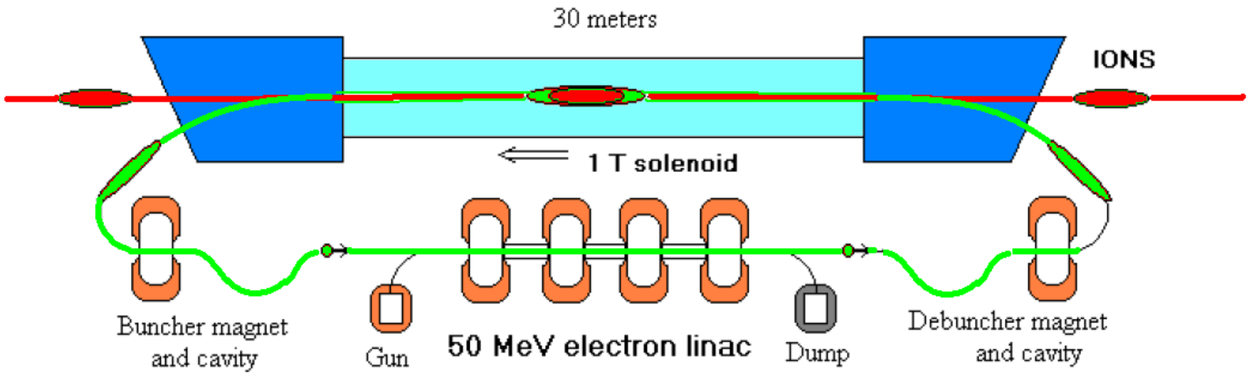
RHIC Upgrade An ongoing effort:

- Bunched beam stochastic cooling A First
  CERN and Fermilab had tried and failed
- Electon Beam Ion Source (EBIS) Already tested
- Design of the highest energy Electron Beam Cooling
  Using "Energy Recovery Linac"

EBIS

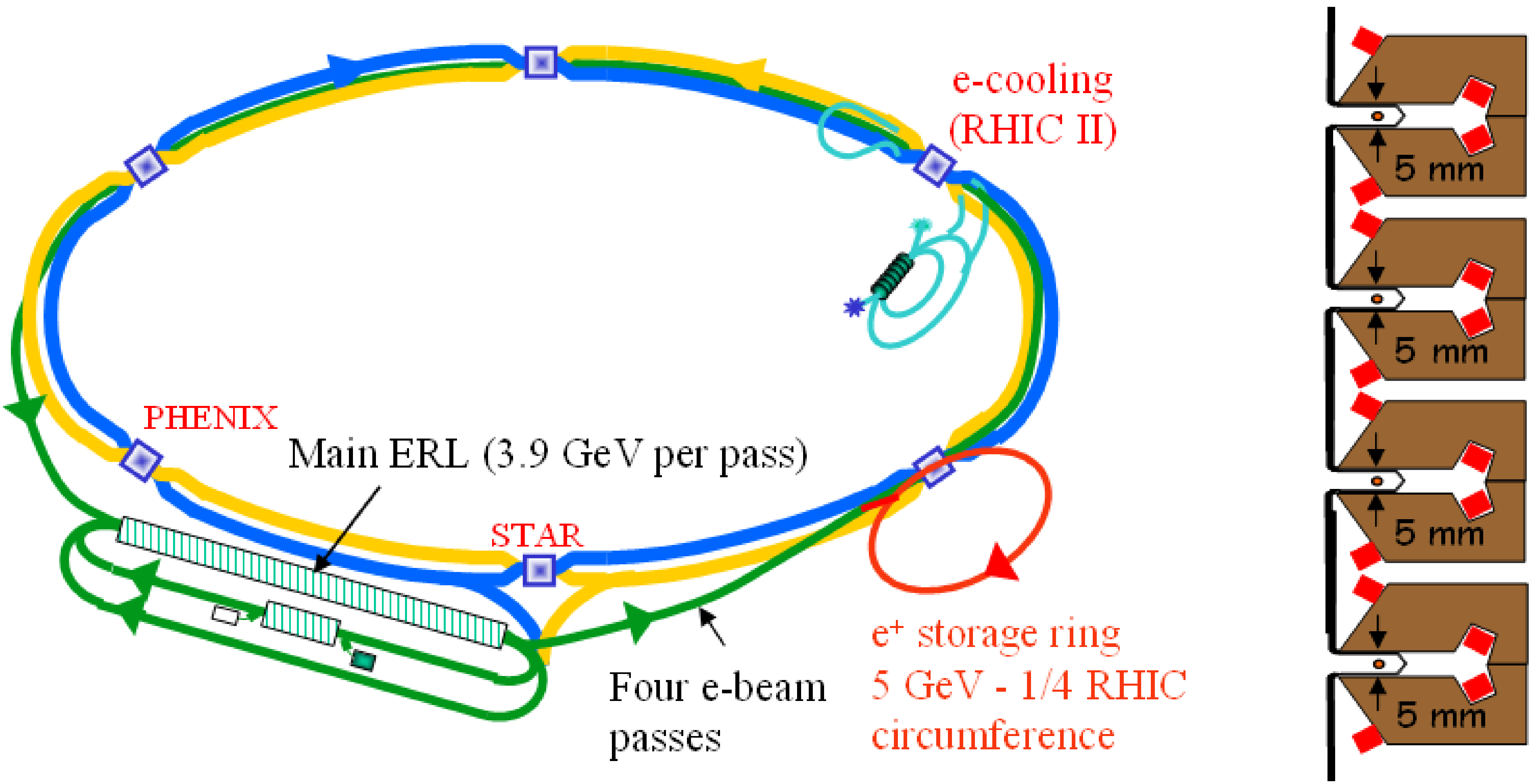


Electron Cooling



BNL Proposed Electron-Heavy Ion Collider: e-RHIC

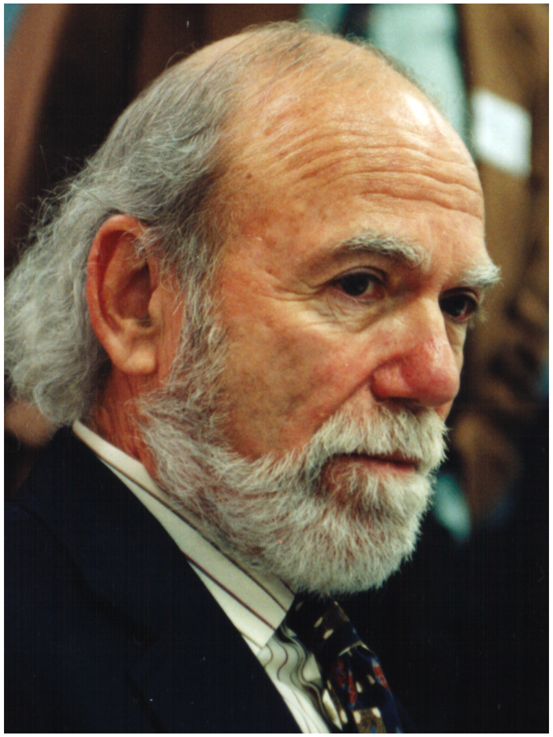
For the future, BNL is proposing to add an electron-Ion capability to RHIC. To get sufficient luminosity a very high electron current is required, again possible using an "Energy Recovery Linac".



Proposed International Linear Collider (ILC)

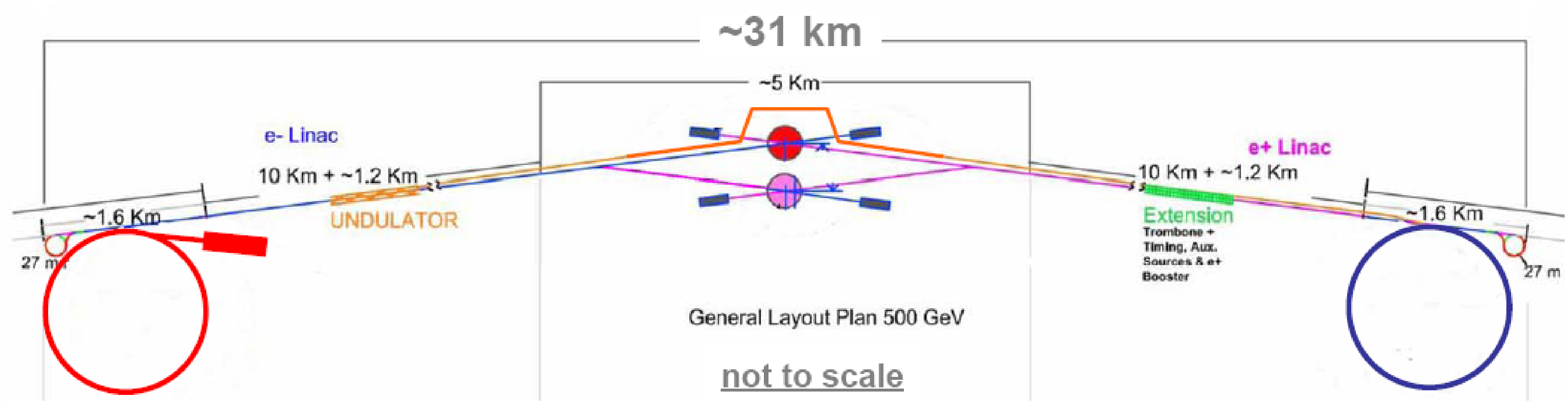
BNL is also contributing to the ILC: an e^+-e^- collider at 250 GeV on 250 GeV.

It is linear because very high energy electrons radiate too much energy when they are bent.



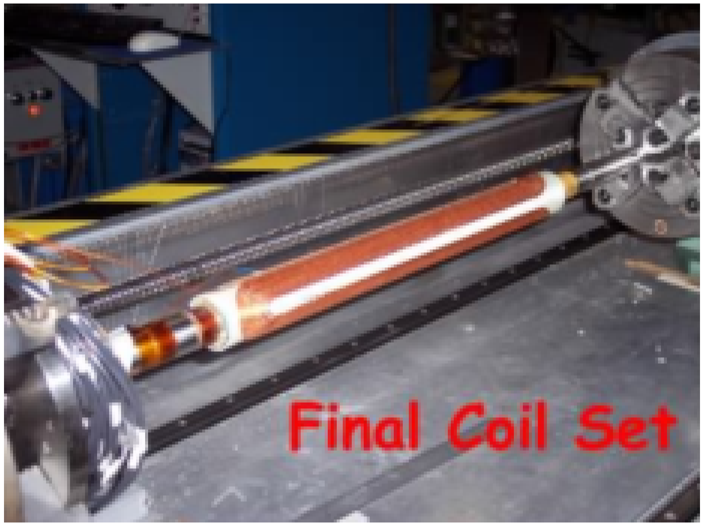
Barish

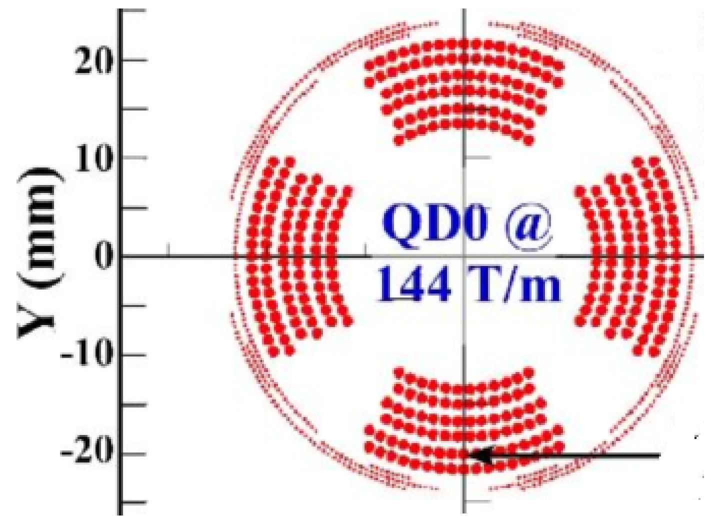
Richter



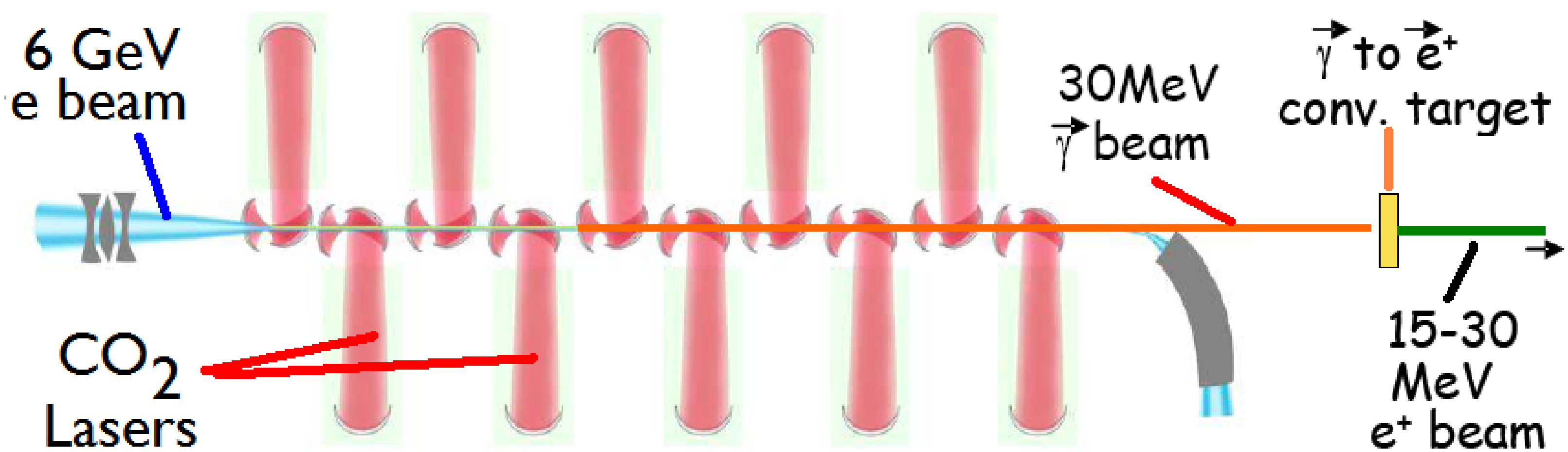
BNL work on ILC   for instance:

- Compact IR Quads   By SC Magnet Group





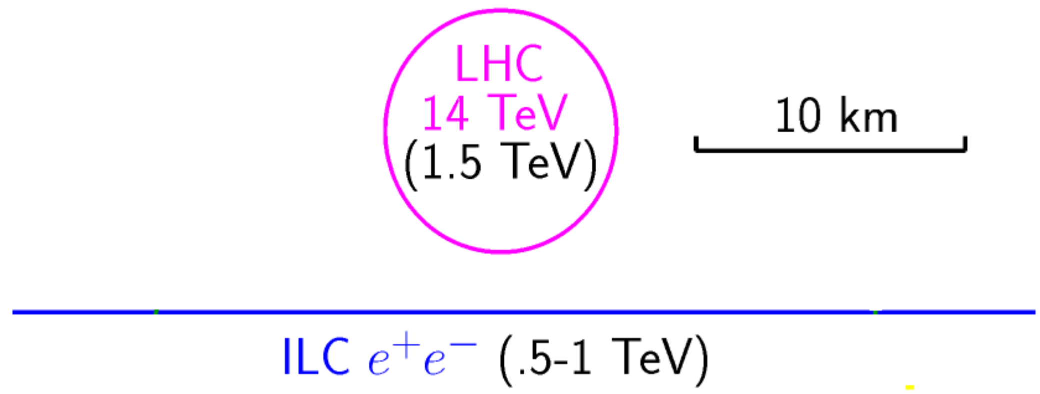
- Polarized e source   by Accelerator Test facility (later)



THE ENERGY FRONTIER

The Energy Frontier Problem

- Because a proton is made of many pieces, The useful interaction energy is less ($\approx 1/10$) than that of the whole
- Electrons or muons are points and their full energy counts



- But electron colliders are harder because one cannot bend high energy electrons in circles
- To go to higher energies without getting bigger:
  - Increase bending fields of a proton collider (BNL SC Magnet Group)
  - Increase acceleration rate in an electron linear collider (ATF)
  - Use Muons which, being heavier, do not radiate so much (1/40,000)

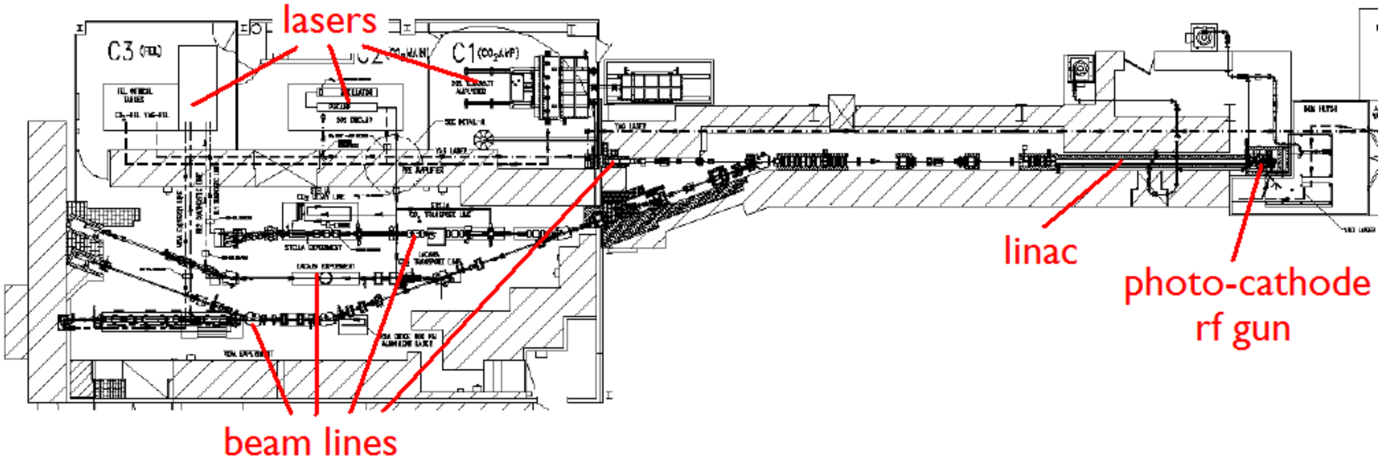
BNL Accelerator Test Facility

Claudio Pellegrini (right) and I founded the only true user facility devoted solely to accelerator physics.

- Low emittance gun
- 70 MeV accelerator
- Yag and CO2 lasers
- User support

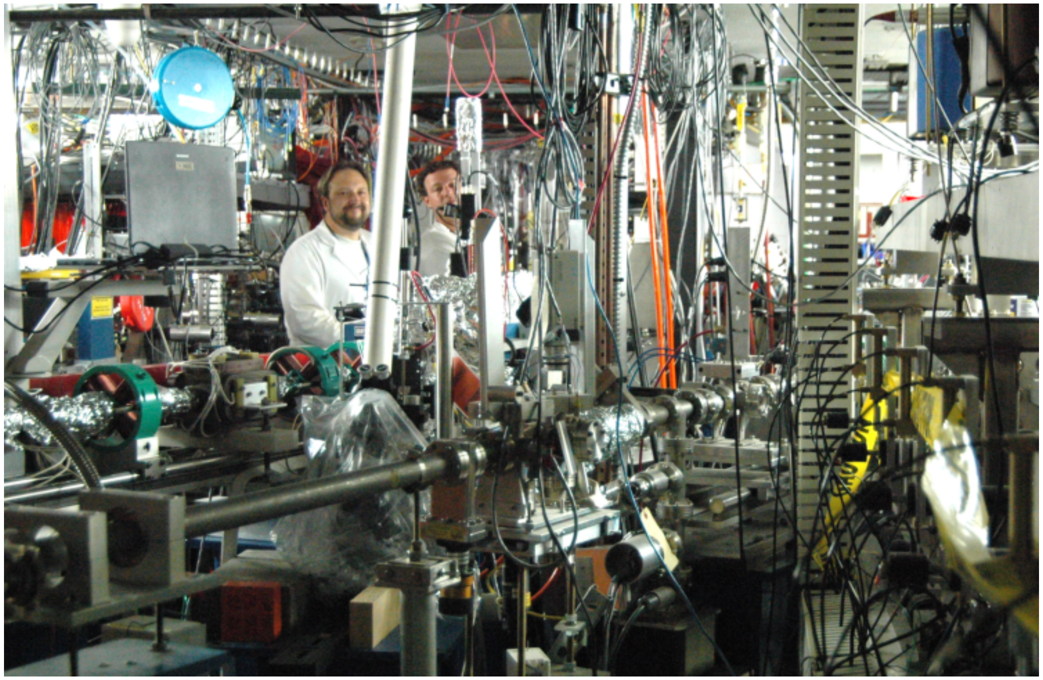
Yakimenko

Ben-Zvi



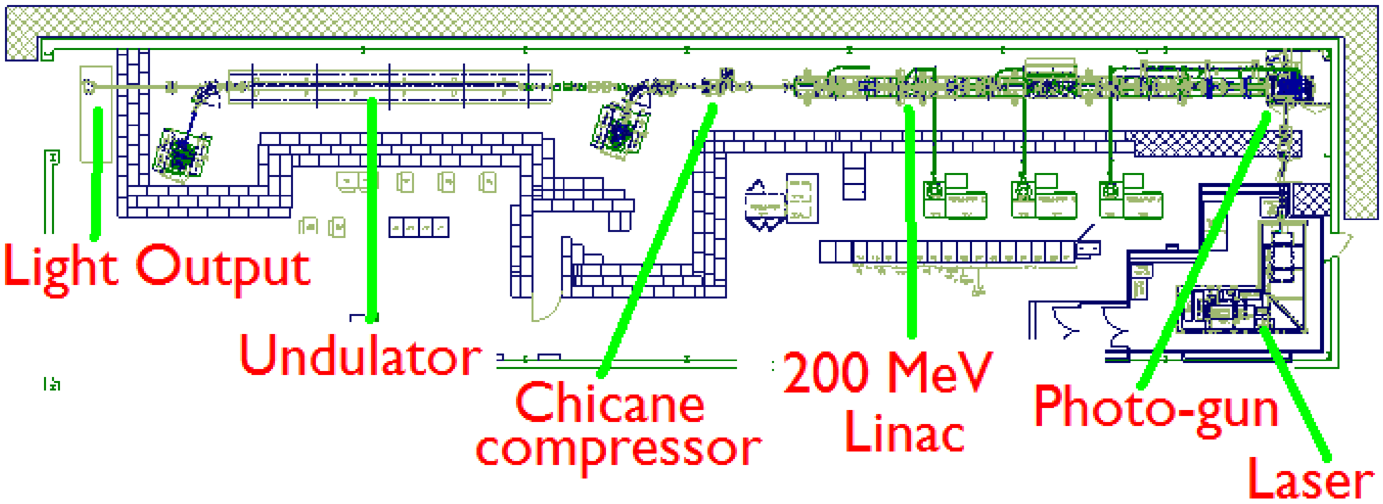
ATF Experiments

- Laser & exotic Acceleration (11)
  - e.g. 2 stage laser acceleration but still far from collider
- Technologies (2)
- Diagnostics(11)
  - e.g. Fempto sec beam detector
- FEL and other light sources (10)

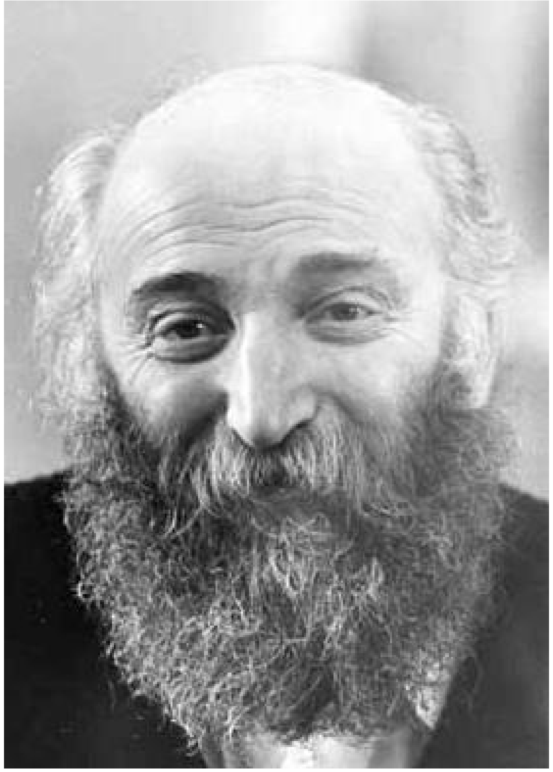


Experimental Hall

- e.g. Harmonic FEL now used in the NSLS Source Development Lab



Muon Colliders



Budker

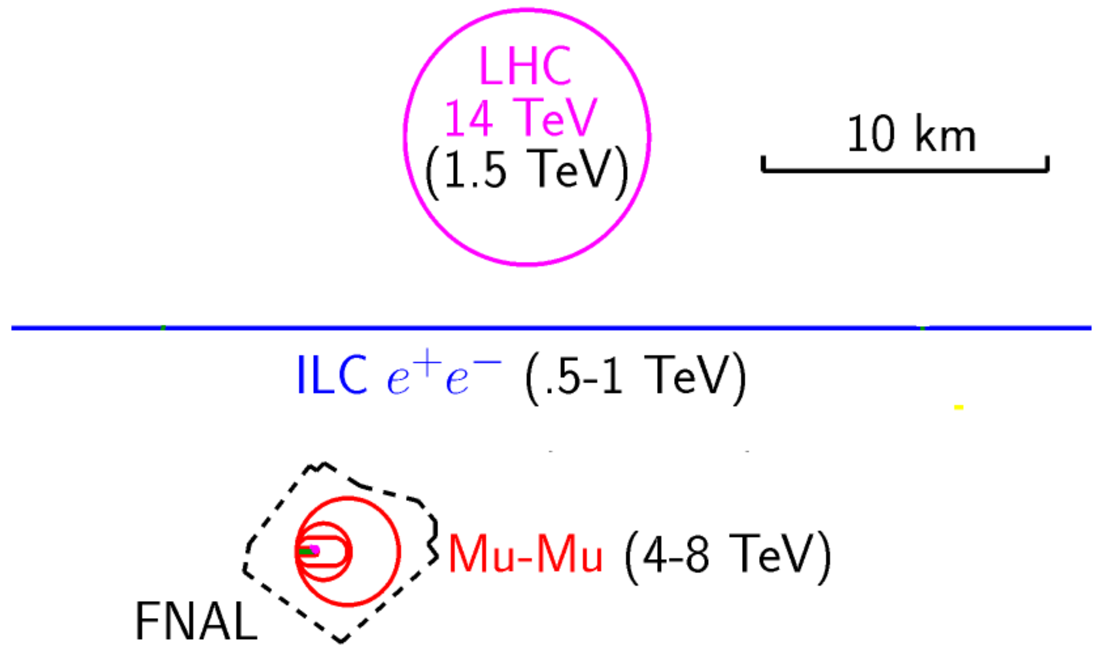
Skrinsky

Neuffer

Proposed by Budker in 1969, with the needed ionization cooling by Skrinsky and Parkhomchuk in 1981. Neuffer gave an outline in 1983. The US Muon Collider Collaboration was formed in 1997. FNAL formed its Muon Collider Task Force in 2006. Much Progress has been made.

Compare with other Colliders

- Because a proton is made of many pieces, The useful energy is less than that of the whole
- Electrons or muons are points and their full energy counts
- But electron colliders are harder because one cannot bend high energy electrons in circles



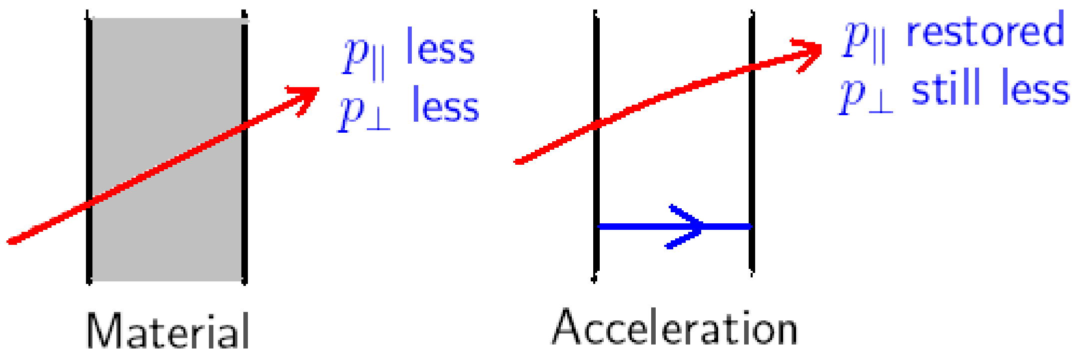
- Muons are point like, so their full energy counts
- And they can be bent, making their colliders much smaller

But life is hard

- Muons are made very diffusely
- And they do not live very long

The problem, as with antiprotons, is cooling the muons
Stochastic cooling is too slow, so we have to use

Ionization Cooling



New technologies are involved. A complete scheme has been outlined, but there is much design and experimental work remaining

BNL is taking a leading role in both design and experiments.

The End

- Thanks to those that helped me
- Apologies to those I left out
- Acknowledgments to
  - Sessler and Wilson's "Engines of Discovery"
  - Crease's "Making Physics"
  - "AGS 20" BNL 51377